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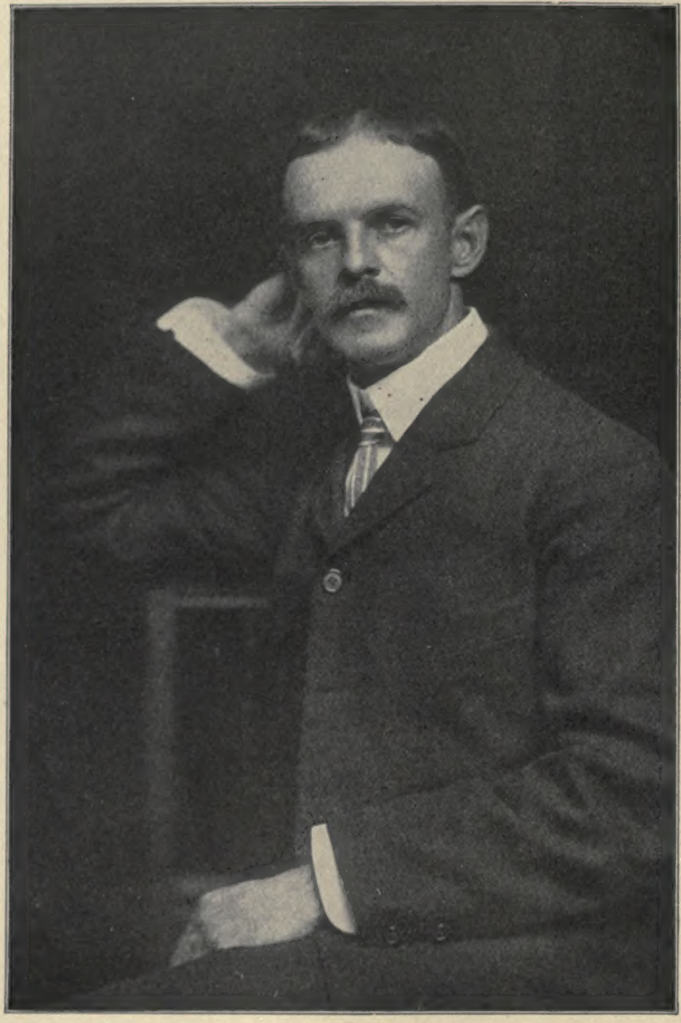

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Cyclopedia
of
Applied Electricity

A General Reference Work

ON DYNAMO-ELECTRIC MACHINERY, GENERATORS, MOTORS, STORAGE BATTERIES, ELECTRIC WIRING, ELECTRICAL MEASUREMENTS, ELECTRIC LIGHTING, ELECTRIC RAILWAYS, POWER STATIONS, POWER TRANSMISSION, ALTERNATING CURRENT MACHINERY, TELEPHONY, TELEGRAPHY, ETC.

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Grateful acknowledgment is here made also for the invaluable co-operation of the foremost engineering firms and manufacturers in making these volumes thoroughly representative of the very best and latest practice in the design, construction, and operation of electrical machinery and instruments; also for the valuable drawings, data, suggestions, criticisms, and other courtesies.

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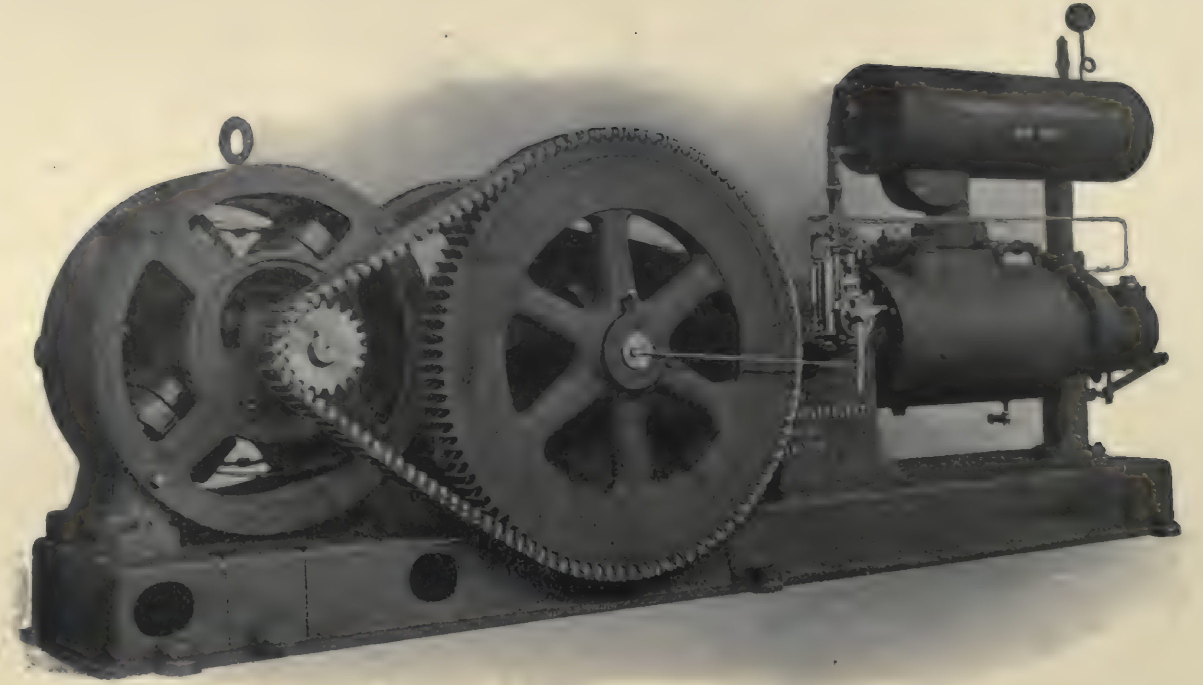

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Foreword

IN view of the great need for a more scientific knowledge of electricity by thousands of practical men of limited technical education, an attempt has been made in the following pages to give a presentation of the subject which will be easily understood by such men, and at the same time cover all essential principles and methods. The principles usually deduced by higher mathematics are here made clear by careful explanation and a large number of diagrams drawn especially to supplement and elucidate the text. Numerous engravings exemplify modern practice, and form a pictorial index to the latest and best methods of applying electricity to lighting, railways, power transmission, the driving of machine tools, etc.

¶ The Cyclopedia of Applied Electricity is based upon the method which the American School of Correspondence has developed and successfully used for many years in teaching practical electricians the scientific principles underlying their work. It is a compilation of representative Instruction Papers of the School, and forms a simple, practical, concise, and convenient reference work for the shop, the library, the school, and the home.

¶ The success which the American School of Correspondence has attained in teaching thousands of electricians, is in itself the best possible guarantee for the present work. Therefore, while these volumes are a marked innovation in technical literature - representing as they do the best ideas and methods of a large number of different authors, each an acknowledged authority in his work they are by no means an experiment, but are in fact based on what has proved itself to be the most successful method yet devised for the education of the busy working man.

¶ Among the sections of especial timeliness are those on Alternating-Current Machinery, Storage Batteries, Electric Wiring, Lighting, etc. In these pages the authors have succeeded in presenting the subjects in such manner as to overcome the hitherto insurmountable obstacle—higher mathematics. The rules and formulæ are presented in a very simple manner, and special effort has been made to illustrate every principle by diagrams, curves, and practical examples.

¶ Numerous examples for practice are inserted at intervals; these, with the test questions, help the reader to fix in mind the essential points, thus combining the advantages of a textbook with those of a reference work.

¶ Grateful acknowledgment is due to the corps of authors and collaborators who have prepared the many sections of this work. The hearty co-operation of these men—engineers of wide practical experience, and teachers of acknowledged ability—has alone made these volumes possible.

¶ The Cyclopedia is published in the belief that it will meet a real need among designers, constructors, and operators of electrical machinery. That it may save many weary hours of search among the scattered textbooks and reference works of the day—books which, being intended largely for college-trained men, are necessarily far from meeting the needs of the average practical man—is the hope of the compilers and publishers.

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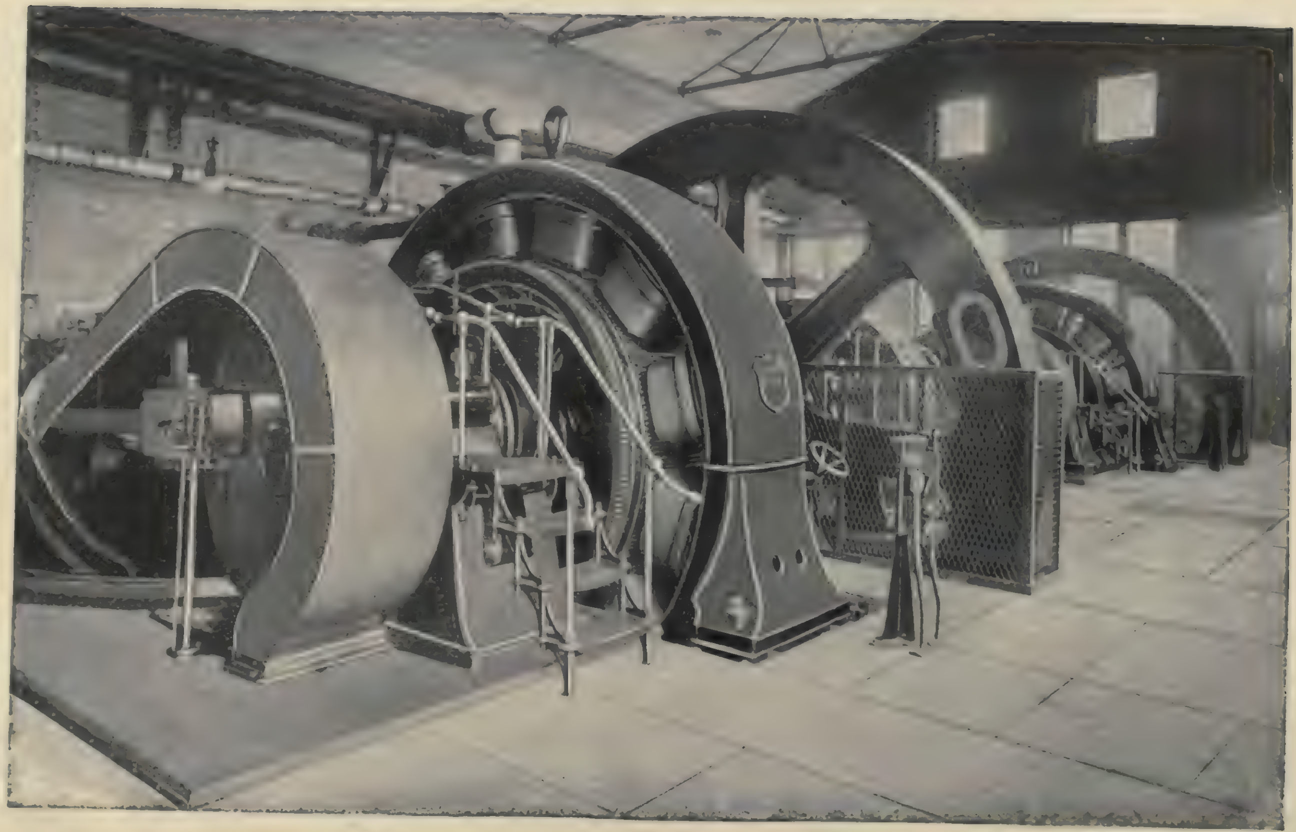

TWO 1,000-K.W. 575-VOLT RAILWAY GENERATORS.
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DYNAMO-ELECTRIC MACHINERY

PART I

PRINCIPLES OF DIRECT-CURRENT DYNAMOS

A *dynamo-electric machine* is one which converts mechanical into electrical energy, or *vice versâ*, by means of the relative motion of a conductor carrying an electric current, and an interlinked magnetic field. When the conversion is from mechanical to electrical energy, the machine is called a *generator;* and when the conversion is from electrical to mechanical energy, the machine is called a *motor*. In order fully to understand the design and construction of these machines, it will first be necessary to consider the principles which govern their action.

Magnetic Field. It was early found that pieces of a certain kind of iron ore were capable of attracting bits of iron. From the name of the country in which this peculiar oxide of iron was first found, came the name of articles made of it—*i.e.*, *magnets*, from "Magnesia," in Asia. This oxide of iron is Fe_3O_4, commonly called *Magnetite.*

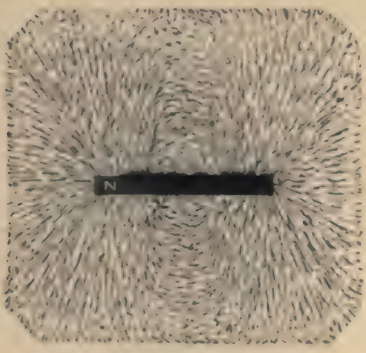

Fig. 1. Magnetic Field around a Bar Magnet.

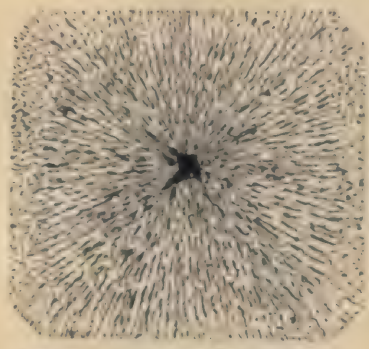

Fig. 2. Magnetic Field around One Pole of a Bar Magnet.

If one of these magnets shaped as a straight bar is held under a piece of cardboard upon which iron filings are sprinkled, it will be found that the filings settle down in curved lines forming a magnetic figure, the general form of which is shown in Fig. 1. When one of the poles of the magnet is held toward the cardboard, the filings will arrange themselves as shown in Fig. 2. These experiments show that the medium surrounding a magnet is in a state of stress, the space so affected being called a *magnetic field.* The influence of a magnet is supposed to extend in all directions indefinitely; *but as the force due to the magnet varies inversely as the square of the distance from it,* the effect is rendered practically negligible beyond a comparatively limited area.

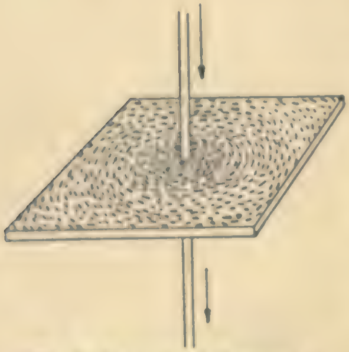

Fig. 3. Magnetic Field around a Current Carrying Conductor.

When a conductor carrying a current of electricity is passed through a piece of cardboard with iron filings sprinkled on the board as before, we see (Fig. 3) that the filings arrange themselves in curved lines similar to those of Fig. 2; while, if the return circuit of the conductor be also poked through the card, the filings assume the alignment shown in Fig. 4. From the similarity of the phenomena, it may be concluded that a conductor carrying an electric current is surrounded by a magnetic field whose strength is a direct function of the current. This was first noted by Oersted, who in 1820 observed that a compass needle was deflected when placed near a conductor carrying a current of electricity, the direction of motion of the needle depending upon the direction of flow of the current.

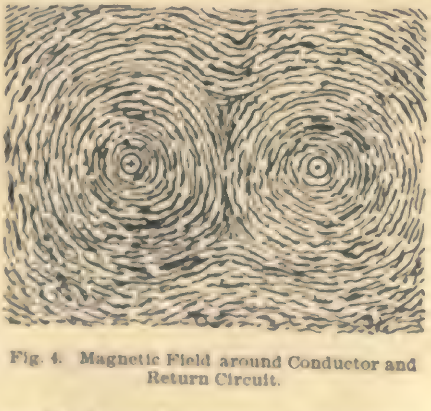

Fig. 4. Magnetic Field around Conductor and Return Circuit.

Lines of Magnetic Force. The magnetic figures in the previous paragraph indicate that the stresses in the medium surrounding a magnet or current-carrying conductor follow certain definite lines, the lines showing the direction of stress at any point. These are called *lines of magnetic force*. If, in addition, there be drawn as many lines per square centimeter cross-section of the field as there would be dynes of force acting upon a unit magnetic pole* placed at that point, then the total number of lines of magnetic force represents the *magnetic flux* through that cross-section; and the lines per square centimeter, the *flux-density*.

Solenoids. Now, suppose that a wire is bent in the form of a circular loop as in Fig. 5, and furthermore suppose that a current is traversing the conductor in the direction indicated. Then, according to a rule suggested by Maxwell,

> "The direction of the current and that of the resulting magnetic force are related to one another, as the rotation and travel of an ordinary (*i. e.*, right-handed) screw."

Consequently the lines of magnetic force would surround the loop in the manner shown. The field of such a loop, on being explored with a compass needle or filings, will be seen to retain the general character of the field surrounding a straight conductor; and consequently all the lines will leave by one face and return by the other, the entire number passing through the loop. Hence one face of the loop will be equivalent to the north pole of a magnet, and the opposite face will correspond to the south pole. In fact the loop will act exactly as if it were a thin disc magnetized perpendicularly to its plane.

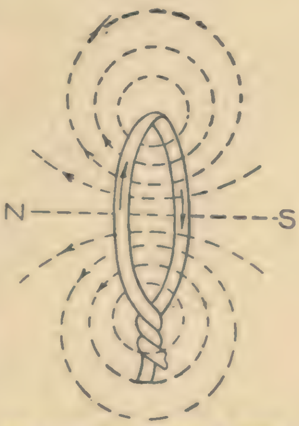

Fig. 5. Magnetic Field around a Conducting Loop.

By placing side by side several of these current loops, with their transverse axes in the same straight line, there is formed a *solenoid* (Fig. 6); and exploration of the resulting field by any of the above methods shows that the lines of force pass right through the interior of the solenoid, leaving by one end and returning by the opposite end as suggested by Maxwell's rule. A cylinder of soft iron inserted in the space within the solenoid will be found to act strongly as a magnet when the current flows around the solenoid; but if the current is interrupted, the magnetic effect almost disappears. Reversal of the current will be found to reverse the polarity of the core, while increasing the current augments the magnetic strength of the coil.

---

* A *unit magnetic pole* is one which, when placed at a distance of one centimeter from a similar pole, in vacuum or practically air, exerts upon it a force of one dyne.

Toroid. Bend the solenoid of the previous paragraph around until its ends meet; or produce the same winding by turning insulated wire around an endless ring core of circular cross-section. The arrangement thus produced will be a *toroid*, commonly called *Faraday's ring;* and if the wires are wound closely and uniformly over the whole periphery, the lines of force will be closed curves whose paths lie entirely within the turns; consequently there are no external poles—a unique electromagnetic condition.

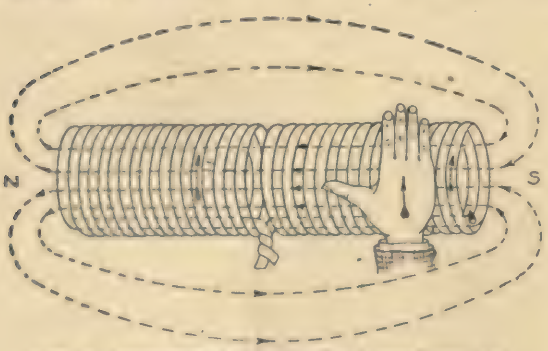

Fig. 6 Arrangement of Conductive Loops Forming a Solenoid, with Surrounding Magnetic Field.

Magneto-Electric Induction. Thus far the condition of the magnetic field has been determined by means of filings or magnets; but neither of these methods can be used to explore the interior of an iron-cored toroid. It is possible, however, to employ for this purpose the principles of *magneto-electric induction* discovered by Faraday in 1831. One of the laws governing this phenomenon, first enunciated by Neumann in such manner as to permit determination of the electromotive force developed, is as follows:

> "Whenever the flux interlinked with a circuit is varying, there is an e. m. f. acting around the circuit, proportional to the time rate of change of the flux, the positive direction of the e. m. f. and the positive direction of the flux passing through the circuit being related to each other as are the rotation and travel of a right-handed screw. That is, if a circular loop is moved in the field of a magnet in such a way that it does not enclose the same amount of flux at any two successive instants, then there is induced in the loop an e. m. f. whose value is proportional to the change of enclosed flux per unit time. A similar effect will be obtained by keeping the loop fixed, and moving the magnet."

We thus have a way to investigate the condition of the field within the solid-cored toroid previously mentioned. Suppose a loop of insulated wire to be placed around the toroid in Fig. 7, and suppose the terminals of this loop to be led to a ballistic galvanometer (that is, an instrument which will measure current impulses). Then if the magnetizing coil of the toroid be energized by passing a current through it, the galvanometer will give a sudden throw the instant the current is started. Similarly, when the circuit is broken and the current ceases, the galvanometer indicates the passage of another current impulse through the loop, the deflection, however, being in the opposite direction.

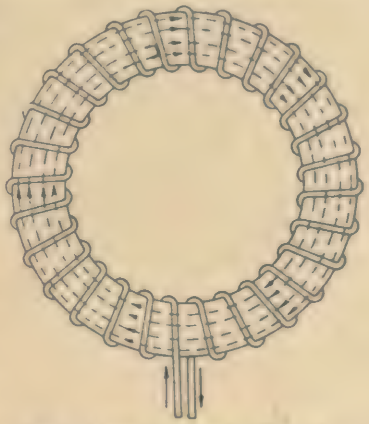

Fig. 7. Lines of Force in Toroid Surrounded by a Magnetizing Coil.

The loop is next removed from the toroid and placed in front of an iron-cored solenoid which can be energized or de-energized at will by closing or opening a switch, and it will be found that similar effects are produced. Let, now, the electromagnet be energized and de-energized periodically, and the loop or exploring coil be turned so that its axis occupies every possible direction in space, the center of the loop remaining stationary throughout. It will be found that when this axis is in one particular plane, no impulse will pass through the exploring coil when the exciting current of the electromagnet is caused to flow, to cease, or to reverse. From what has been explained previously, we see that in this case the loop interlinks with no flux, hence its plane must be parallel to the direction of the flux. Also we see that when the plane of the loop takes any other position, the flux interlinked with it depends upon the relation between the plane of the loop and the direction of the flux. If we call the angle between the direction of the flux and the axis of the loop a, the flux enclosed by the loop for any given value of the exciting current of the electromagnet will be proportional to the cosine of a. The quantity we are thus investigating is a directed quantity, and may therefore be represented by a vector.

Lines of Magnetic Induction. This quantity is called the *magnetic induction* or *flux*, and its direction at any point is defined as that of the axis of the loop when in the position giving the greatest inductive effect on energizing or de-energizing the electromagnet. Its direction is also defined by Neumann's law. If, now, a curve be drawn following the direction of the flux, this curve will be a line of magnetic induction. The flux and flux-density are defined in a way precisely similar to magnetic force.

Relation between Magnetic Force and Magnetic Induction. In the earliest of Faraday's experiments with solenoids, he found that the flux through any of these was much greater when iron was inserted than when air or wood was enclosed by the coil of wire. He ascribed this peculiar circumstance to the greater "conducting power of the magnetic medium for lines of force." Lord Kelvin introduced the phrase *magnetic permeability* for this property of magnetic materials, and it is defined as the ratio between the magnetic induction (B) produced in the medium and the magnetic force (H) to which that induction is due; *i. e.*,

$$\mu = \frac{B}{H}.$$

Magnetic Permeability. The precise notion now attached to this term is that of a numerical coefficient, and it is analogous to electrical conductivity. Its value is dependent upon the character of the substance and the magnetizing force or m. m. f. applied to the substance. For vacuum its value is unity; for air it is practically unity; for magnetic materials it is greater than 1 and may reach 2,500 for soft iron; while for diamagnetic materials it is slightly less than 1. The permeability of such non-magnetic materials as silk, cotton, and other insulators, also of brass, copper, and other non-magnetic metals, is taken as unity, being practically the same as for air.

The permeability of iron, however, varies very greatly with the degree to which it has been magnetized. In all kinds of iron (after passing the initial stage mentioned below), the magnetizability of the material becomes diminished as the actual magnetization is pushed further; in fact, there is a tendency to magnetic saturation. In other words, when the piece of iron has been magnetized up to a certain degree, it becomes less permeable to further magnetization; and although actual saturation is never reached, there is a limit beyond which the magnetization cannot be increased with practical advantage. This is shown in Fig. 8, which represents the permeability curve of a sample of good iron or steel as used in dynamo magnet construction. The practical limit of the flux-density (*B*) in good wrought iron and in mild steel, is about 20,000 lines of magnetic induction per square centimeter; and in cast iron the saturation limit in practice is about 12,000 lines per square centimeter. In square-inch units these limits are, for wrought iron and mild steel, about 125,000 or 130,000 lines per square inch; and for cast iron, about 70,000 lines per square inch.

Magnetic Circuit. Returning to the toroid of Fig. 7, we see that the lines pass through the interior of the toroid, forming a closed magnetic circuit. Now, it is found that the total flux within the toroid is equal to the ratio between the magnetomotive force acting around the magnetic circuit and the reluctance of that circuit; that is

$$\phi = \frac{\text{m. m. f.}}{R},$$

in which,

ϕ = Total flux;

m. m. f. = Magnetomotive force;

R = Magnetic reluctance.

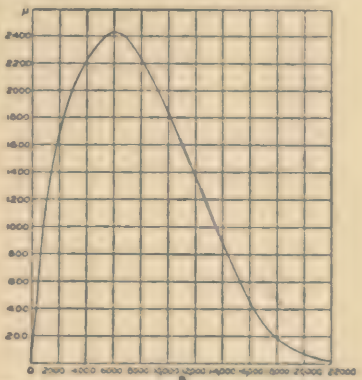

Fig. 8. Permeability Curve of Iron or Steel Used in Dynamo Magnet Construction.

Magnetomotive Force. By this term is meant the total magnetizing power of an electric current circulating in a coil. It is found, when a current flows in a wire wound several times around a core, as in Fig. 9, that the magnetizing power is proportional both to the strength of the current and to the number of turns of wire. The magnetizing power is independent of the size of the wire or the coils and of their shape, remaining also the same whether the spirals are close together or wide apart. Hence if *T* be the number of turns in the coil, and *I* be the current in amperes passing through each turn, the magnetomotive force is,

$$\text{m. m. f.} = \frac{4}{10}\,\pi \times I\,T = 1.257\,IT.$$

A straight conductor carrying an electric current of which the return is very distant, as in Fig. 10, is surrounded by circular concentric lines. Taking one of these lines at a distance r centimeters from the axis of the wire, which we suppose to be carrying I amperes (that is, $\frac{I}{10}$ units of current in C. G. S. electromagnetic units), the intensity of the field at any point at radius r has the uniform value $\frac{2I}{10r}$, and its direction is that of the given line, of which the length is $2\pi r$. Hence the total force around the circle of radius r concentric with the axis of the conductor, will be the product of the force at any point of its circumference into the length of this circumference; *i. e.*,

$$\frac{2I}{10r} \times 2\pi r = \frac{4\pi}{10} I.$$

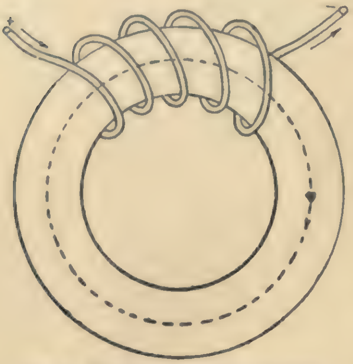

Fig. 9. Showing Relation between Magnetizing Power of a Coil and Its Number of Turns.

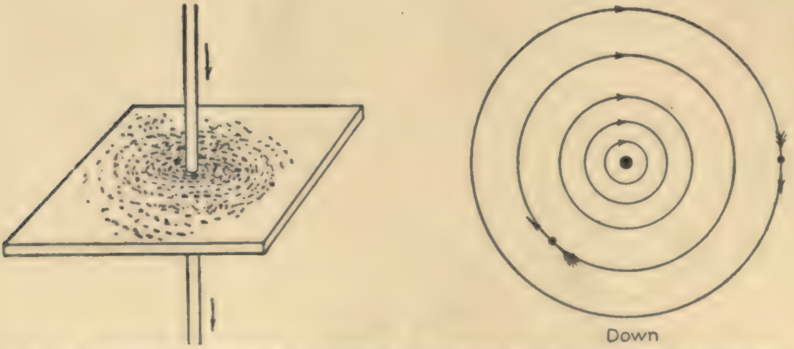

Fig. 10. Illustrating Variation in Intensity of Magnetic Field Surrounding a Conductor with Distant Return.

And if the single wire be replaced by T turns, the force will be T times as large, or $\frac{4\pi}{10} I\,T$, $I\,T$ being called the *ampere-turns*.

Reluctance. We have seen from the equation of the magnetic circuit, that the total flux is inversely proportional to the reluctivity of the materials of which it is composed; it is directly proportional to the permeability which is the reciprocal of the reluctivity. The reluctance or magnetic resistance of a circuit is therefore obviously proportional to its length, and inversely proportional to its area of cross-section and its permeability; that is,

$$R = \frac{l}{\mu A}$$

In designing electromagnets, before calculations can be made as to the size of the iron core required, it is necessary to know the magnetic properties of that particular iron; for it is obvious that inferior permeability demands a larger cross-section to obtain a given flux, or inferior permeability will require more turns of copper wire to be used.

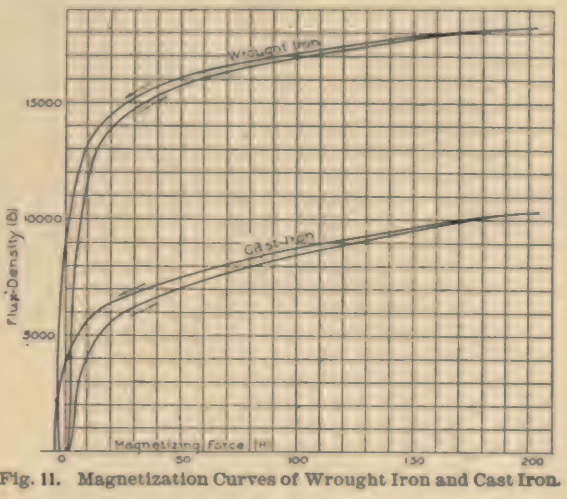

Fig. 11. Magnetization Curves of Wrought Iron and Cast Iron.

Magnetization Curves. A convenient method of studying the magnetic facts respecting any particular brand of iron, is to plot as a diagram the *curve of magnetization*—that is, the curve representing the relation between the magnetic force plotted horizontally, and the magnetic induction plotted vertically.

The upper curve in Fig. 11 gives the behavior of annealed wrought iron. The ascending curve shows the relation between the intensity of the magnetizing force H and the flux-density B during the process of increasing the magnetizing force from zero to about 210 units; and the descending line shows the same relation during the process of decreasing the magnetizing force to zero, and then reversing it so as to remove the residual magnetic lines. The lower curve shows the behavior of grey cast iron.

Every sample of iron will show a similar set of results, which can be plotted in the form of a curve that is characteristic. The curves for cast iron and hard steel always have lower values than those for wrought iron or mild steel. In addition, it will usually be noted that when a fresh piece of iron or steel is subjected to a gradually increasing magnetizing force, the lowest part of the curve presents near its origin a small concavity (see Fig. 11), showing that under certain magnetizing forces the permeability is greater than at the initial stage. This concavity is more pronounced in the case of hard iron and steel than in the case of soft iron, but the curves differ in detail even in different specimens of the same sort of iron.

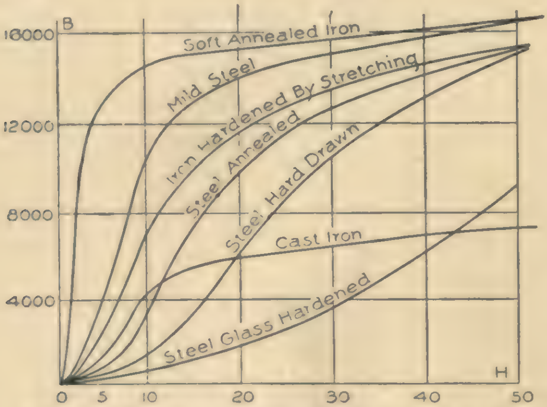

Fig. 12. Magnetization Curves of Various Irons and Steels Used in Dynamo Construction.

Fig. 12 gives a comparative idea of the relation between the magnetic properties of the various irons and steels used in dynamo manufacture.

Effect of Air-Gap in Magnetic Circuit. Thus far we have considered the magnetic circuit as made up of a solid, endless ring of iron. But suppose it to be built up partly of iron and partly of some non-magnetic material, as air or copper. We then have, as the total reluctance of the magnetic circuit, the sum of the reluctances of the various parts of the circuit. For example, if we have a ring made up of l_i centimeters of iron and l_a centimeters of air, the reluctance of this magnetic circuit would be,

$$R = \frac{l_i}{\mu_i A_i} + \frac{l_a}{\mu_a A_a},$$

in which μ and A are respectively the permeability and cross-sectional area of the materials denoted by the subscripts.

It follows, then, that the total flux of such a circuit would be,

$$\phi = \frac{0.4 \pi I T}{\dfrac{l_i}{\mu_i A_i} + \dfrac{l_a}{\mu_a A_a}},$$

in which $I T$ represents the ampere-turns and $.4 \pi = 1.257$ as before.

Since the magnetic permeability of air is constant and practically equal to unity, we see that an air-gap or its equivalent introduced into a magnetic circuit previously consisting of iron, will increase the m. m. f. required to produce the same flux as before, due to the inferior permeability of the non-magnetic portion.

S. P. Thompson makes this plain by a graphical method as follows:

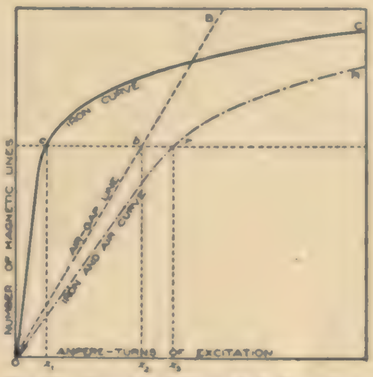

Fig. 13. Graphical Method of Showing Effect of Air-Gap in a Magnetic Circuit.

> "The curve *OcC* (Fig. 13) represents the relation between the number of magnetic lines in an iron bar and the ampere-turns ($= Hl \div 1.257$) needed to force these magnetic lines through the iron. For example, to reach the height *c*, the excitation has to be of the value represented by the length Ox_1. On the same diagram the line *ObB* represents the relation between the magnetic flux across the air-gap and the ampere-turns of current (stream) required to force this flux across. If the gap were 1 centimeter long, 0.795 ampere-turn would produce the field $H = B = 1$. In the present case the gap is supposed to be shorter than 1 centimeter, the line sloping up at such an angle that the length Ox_2 represents the ampere-turns requisite to bring the magnetic flux up to *b*, the same height on the scale as *c*. The total amount of excitation required to force these magnetic lines through air and iron will (neglecting leakage) be the sum of the separate amounts. The point x_3 is chosen so that Ox_3 is equal to the sum of Ox_1 and Ox_2, or that the distance of the point *r* from the vertical axis is equal to the sum of the respective distances of *c* and *b*. If the same thing is done for a large number of corresponding points, the resultant curve *OrR* may be constructed from the two separate curves. It will be seen, then, that in general the presence of a gap in the magnetic circuit has the effect of causing the magnetic curve to rake over, *the initial slope being determined by the air-gap.*"

Effect of Joints in the Magnetic Circuit. Ewing* tried the effect of different numbers of joints in the iron of a magnetic circuit for various magnetizing forces, his results being given in Fig. 14. They refer to a bar of wrought iron cut across, first into two pieces, then into four, and finally into eight pieces. He also found that when the faces of a cut were carefully surfaced up to true planes, the disadvantageous effects of the cut were considerably reduced, and under considerable pressure applied externally almost vanished. An ordinary joint is equivalent to an air-gap of about .005 cm. = .002 inch.

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* "Magnetic Induction in Iron and Other Metals," London, 1892, pages 208 to 273.

Effects of Heat. When iron is raised to 600°C., it begins to lose its magnetic properties; and, if the temperature is increased to 780°C., they entirely disappear. At temperatures between 0°C. and 100°C., various other effects have been noted, such as *aging*—that is, an increase in the hysteresis. In dynamos, however, these effects are practically negligible, since the working temperature should not exceed 75°C.

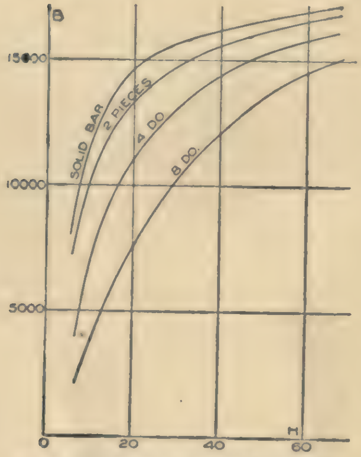


Fig. 14. Curves Showing Effects of Joints in Magnetic Circuit.

Residual Magnetism. It has been found, when the magnetizing forces have been removed from a specimen of iron, that it still exhibits some phenomena of magnetism. This residual magnetism depends for its magnitude upon the character of the iron or steel, being greater in the harder grades than in the softer ones.

Referring to Fig. 11, it will be seen that when a specimen of wrought iron was magnetized to a high flux-density, and the m. m. f. then reduced to zero, the flux-density diminished only to about 7,300 lines per square centimeter, the descending curve of magnetization being above the ascending one. The name *remanence* is given to the lines per square centimeter so remaining. Furthermore, in order to remove this remanence, it is necessary to apply a certain negative magnetizing force, termed by Hopkinson the *coercive force*. It varies in magnitude from 2 for soft wrought iron, to about 80 units or more for hard steel.

Effects of Cycles of Magnetization. This tendency of the magnetic effects to lag behind the forces producing them has been named by Ewing *hysteresis*, and is best studied by subjecting the iron specimen to one or more complete cycles of magnetization. For instance, suppose the m. m. f. applied to a piece of iron to be increased gradually from zero to a maximum value, then decreased through zero to an equal negative maximum, and finally to reverse and return through zero to the positive maximum value. The magnetic changes for such a complete cycle are shown in Fig. 15 for specimens of iron and steel respectively.

The process as shown by the diagram, is started with the flux-density and m. m. f. at zero. The latter is then increased to about 60 units, in the case of the piece of iron, the resulting flux-density being 16,000. The m. m. f. is then reduced to zero, the flux-density only decreasing to 12,800. At a m. m. f. of –3, the flux-density is brought to zero; that is, –3 is the coercive force, and 12,800 the remanence. With a m. m. f. of – 60, the flux-density is – 15,500; and varying the m. m. f. from this point to zero, leaves the specimen with a flux-density of – 12,000. Further increasing the m. m. f. until the flux-density becomes zero, the final m. m. f. is found to be + 3. From this point the m. m. f. is increased to its former maximum value, this ascending curve differing a little from the first. Thus we see that when a specimen of magnetic material is put through a complete magnetic cycle, the coincident values of the m. m. f. and the flux-density form a close curve. The area thus enclosed has been shown by Warburg and Ewing to represent the energy wasted as

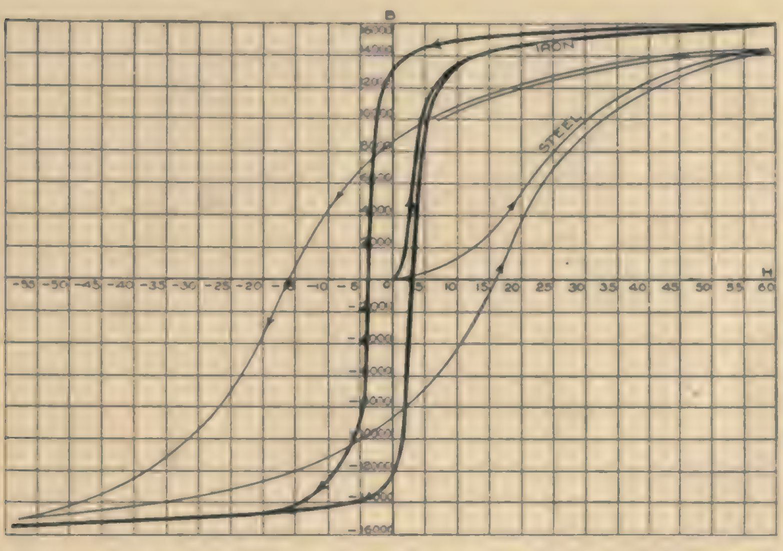


Fig. 15. Curves Showing Magnetic Changes in Iron and Steel Due to Complete Cycles of Magnetization.

TABLE I

Hysteretic Constants for Different Materials

MATERIAL	HYSTERETIC CONSTANT η	MATERIAL	HYSTERETIC CONSTANT η
Very soft iron wire........	.002	Soft annealed cast steel...	.008
Very thin soft sheet iron...	.0024	Soft machine steel........	.0094
Thin good sheet iron.......	.003	Cast steel...............	.012
Thick sheet iron..........	.0033	Cast iron................	.016
Most ordinary sheet iron...	.004	Hardened cast steel.......	.025
Transformer cores.........	.0045		

heat in the material, when the specimen is put through a complete cycle; and its value depends upon both the character of the material, and the degree of magnetization, being greater for hard steel than for soft iron with the same range of magnetization.

Iron, when placed in an alternating magnetic field, is not only subjected to the hysteresis phenomena above considered, but it also becomes subjected to a set of parasitic electrical currents. These tend further to heat the iron, and are called *Foucault* or *eddy currents;* their path, by Maxwell's law, is perpendicular to the direction of the flux. Their value may be lessened by increasing the resistance of their path—that is, by *laminating the iron in a direction parallel to the direction of the flux and perpendicular to the path of these currents,* each sheet of iron being insulated from its neighbors. In practice, these laminæ vary from about 15 to 25 mils (0.015 inch to 0.025 inch) in thickness.

Calculation of Heat Waste in Iron Cores. From consideration of a great many tests of hysteretic losses, Dr. C. P. Steinmetz proposed the following law connecting the hysteresis loss h in ergs per cubic centimeter per cycle and the maximum flux-density B attained during a cycle:

$$h = \eta B^{1.6},$$

wherein η is a coefficient called the *hysteretic constant,* depending for its value upon the quality of the material. Some of these constants are given in Table I for ordinary frequencies. This law is practically true for all cycles ranging up to 200 per second.

By applying the proper transformation factors, the Steinmetz formula reduces to:

$$W_h = 0.83 \times \eta \times f \times B^{1.6} \times 10^{-7},$$

wherein

W_h = Hysteresis loss in watts per cubic inch of iron;
f = Frequency in cycles per second;
B = Flux-density in lines per square inch.

In Fig. 16 are given graphically the hysteresis losses in watts per cubic inch of iron per cycle per second, with various hysteretic constants.

Besides the hysteretic loss in iron cores, there is also the eddy-current loss, which varies directly as the square of the thickness of the iron laminæ, as the square of the maximum flux-density, and as the square of the frequency. The formula obtained by calculation and found to agree closely with practice, is:

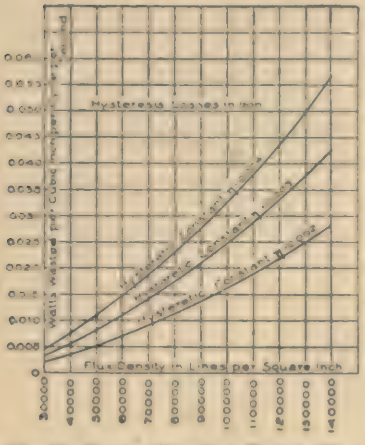


Fig. 16. Curves Showing Hysteresis Losses in Iron with Various Hysteretic Constants.

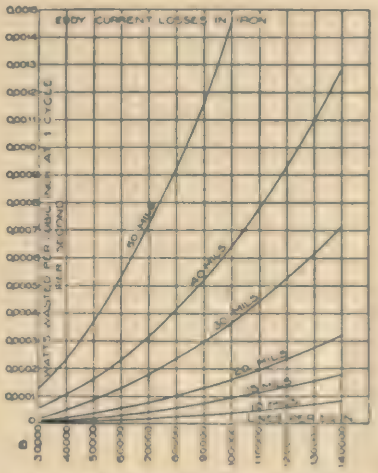


Fig. 17. Curves Showing Eddy-Current Losses in Iron of Varying Thickness under Varying Flux-Density.

$$W_e = 40.6 \times t^2 \times B^2 \times n^2 \times 10^{-12},$$

wherein

W_e = Watts loss due to eddy currents per cubic inch of iron;
t = Thickness of the iron plates, in inches; and the other symbols have the meanings previously assigned.

Fig. 17 exhibits values of W_e graphically for various thicknesses of iron over wide ranges of flux-density at one cycle per second.

The sum of these losses for any electrical machine is called for brevity the *iron-losses* of that machine. Calculations for actual machines will be given later.

Rotational Hysteresis. When a piece of iron is rotated in a magnetic field, it passes through a magnetic cycle, but in a way far different from that which has been described. Mordey found the losses to be slightly lower for rotation than for reversal; while Baily went further and showed (Fig. 18) that the former loss was slightly greater than the latter for flux-densities up to 15,000 lines per square centimeter, but that beyond this point the loss due to rotation rapidly diminished with increase in flux-density.

Owing, however, to eddy-current losses, the flux-densities in those parts of electrical machines which rotate in a fixed magnetic field are not allowed to exceed 15,000 lines per square centimeter (15,000 × 6.45 lines per sq. in.), except in the armature teeth of direct-current machines. We may therefore neglect this difference, as is usual in practice, and may calculate both kinds of hysteresis loss by the formula previously given. According to Ewing, this rotation loss is *molecular magnetic friction* and not true hysteresis, because the magnetization does not necessarily lag behind the m. m. f.

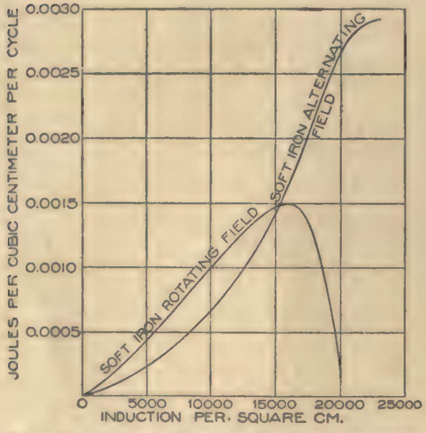
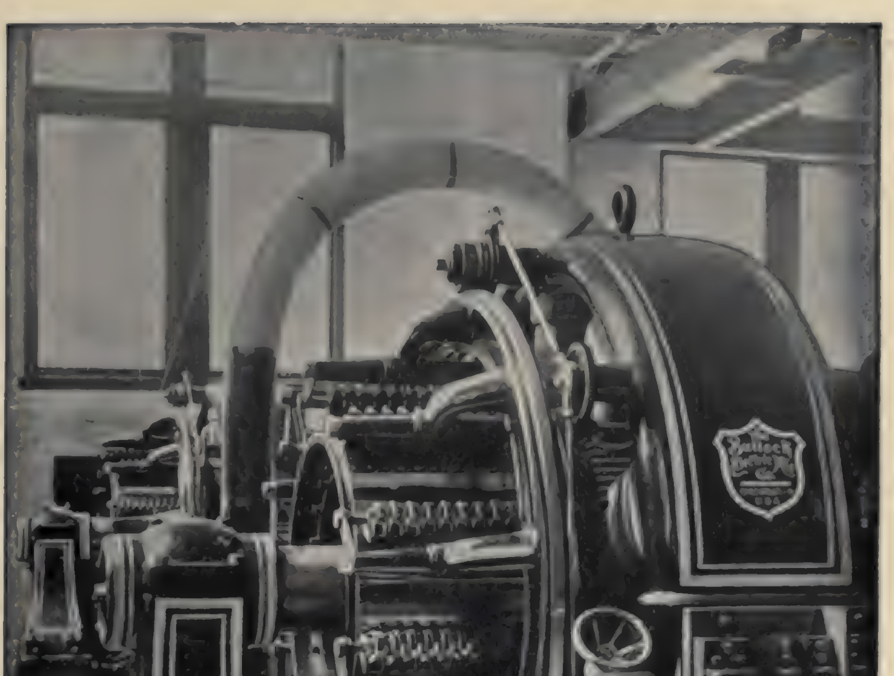


Fig. 18. Curves Showing Relation between Hysteresis Losses in Rotating and Alternating Fields.

Miscellaneous Magnetic Effects. *Retardation of Magnetization.* It has long been known that, owing to the eddy currents produced in the iron cores of electromagnets, the magnetism of the inner part builds up less rapidly than that of the outer parts. Similarly, when the m. m. f. is cut off, the inner part of the core retains its magnetism longer than the outer parts. In dynamos with large field-magnets, several minutes may elapse before the field will build up or change, and Hopkinson has shown that the retardation varies as the square of the linear dimensions of the core.

Magnetic Creeping. Ewing found that when a steady m. m. f. was applied to a specimen of iron, and the magnetism measured at intervals, the flux-density kept continually creeping up although



250 K.W. ENGINE-TYPE GENERATOR

at Prudential Life Building, Newark, N. J.

Bullock Electric Manufacturing Co.

the m. m. f. was absolutely constant. He named this *viscous hysteresis;* but it is a true magnetic lag, and must not be confounded with the lag in phase resulting in the formation of a loop, or the lag due to self-induction occasioned by eddy currents in the iron.

Slow Changes in the Magnetic Properties of Iron. When iron is continually subjected to rapidly alternating flux-densities, especially when the temperature rises above 100°C.,it is found that the hysteretic loss is perceptibly increased. This effect has been observed in connection with transformers, where the iron losses play an important part in the working; but in continuous-current dynamos and motors the effect is negligible. (See page 12).

Magnetic Dampers. If a magnetic flux, whether in air or iron, be surrounded by a closed electrical circuit, any change in the value of the flux will induce an e. m. f. in that metallic circuit, tending to oppose the flux change. It has suggested itself, therefore, to builders of dynamos, to surround the magnet-poles with copper bands in order to reduce the possibility of sudden field fluctuation. This feature is employed extensively in alternating-current generators, synchronous motors, and rotary converters, under the name of *dampers* or *damping rings.*

Generation of E. M. F. by Cutting Flux. Whenever lines of magnetic flux are cut by a conductor, an e. m. f. is produced in that conductor, the value of the e. m. f. being one volt when 100,000,000 or 10^8 lines are cut per second. In other words, the e. m. f. depends solely upon the *time rate* of cutting, so that one volt would also be set up if 10^6 lines were cut in one-hundredth of a second. In both cases the time rate of cutting is supposed to be uniform throughout the given time.

The generation of e. m. f. is absolutely certain, no matter when or by what process the lines are cut. A *current*, however, will flow only when there is a closed electrical circuit. A straight bar of copper, for example, cutting across a magnetic field, would have a potential difference established between its ends; but, excepting a slight displacement current at the start, no current would flow until the electrical circuit was completed. We should distinguish, therefore, between the generation of an e. m. f. and the flow of a current. Thus, it may happen that two or more opposing voltages neutralize each other, so that no current whatsoever flows, even though the electrical circuit is complete. This is the case when a copper ring is moved in its own plane across a uniform field; the two halves cut an equal number of lines, and the e. m. f. produced in one half is exactly equal but opposite to that produced in the other half of the ring, making the current-flow zero. This explains the fact that the flux in a coil of wire must be varied in order to permit a current to flow; or, in other words, the coil must be filled with and emptied of, lines of magnetic induction, in which case an alternating current is produced. This is often stated so broadly, however, that it seems to mean that an e. m. f. cannot be obtained in a uniform field. As already stated, an e. m. f. *must* be produced whenever magnetic lines are cut, though a flow of current may not result.

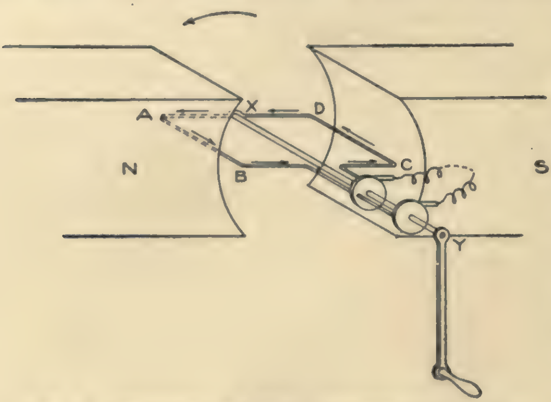


Fig. 19. Illustrating the Elementary Principles of the Generator.

Elementary Generator. The simplest form of generator consists of a loop of wire arranged to rotate in a uniform magnetic field, Fig. 19. The generation of e. m. f. in such a dynamo will be as follows: Assume the loop with its plane parallel to the direction of the flux. If, then, the loop be rotated counter-clockwise about its axis XY, the sides AB and CD, which cut lines of magnetic induction, will have an e. m. f. induced in them that will tend to cause a current flow in the directions indicated by the arrows. The value of this e. m. f. will depend upon the speed or *time rate* of cutting; and since this rate is greatest when the plane of the loop is parallel to the direction of the flux, the e. m. f. developed at the instant represented in Fig. 19 will be a maximum. As the loop approaches the 90° or vertical position, the generated e. m. f. gradually decreases because the rate of cutting is diminishing, until, at the 90° position, the cutting of the flux and the generated e. m. f. are both zero. If the rotation is continued, the rate of cutting gradually increases until the 180°

position is reached, where it again becomes a maximum, so that the e. m. f. generated at this intant is also a maximum. The cutting, however, in the two quadrants following the 90° position, has been in the opposite direction to that occurring in the first quadrant, so that the direction of the e. m. f. generated in the second and third quadrant is reversed with respect to that generated in the first quadrant. In passing from the 180° position to the 270° position the rate of cutting and the generated e. m. f. again diminish to zero; and from 270° to the 360° or 0° position, the rate of cutting increases and the direction of the generated e. m. f. is the same as that produced in the first quadrant, the e. m. f. rising once more to a maximum value at the 360° position.

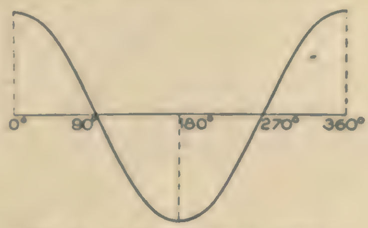


Fig. 20. E. M. F. Curve of Simple Generator Shown in Fig. 19.

Plotting the various instantaneous values of the e. m. f. so generated, we obtain the curve shown in Fig. 20. Such an e. m. f. is called an *alternating* one, because of its reversal from positive to negative values; that is, it tends to produce a current, first in one direction and then in the other direction, through the circuit. If, however, it is desired to supply the external circuit with a direct or continuous current, a special rectifying device called a *commutator* must be added.

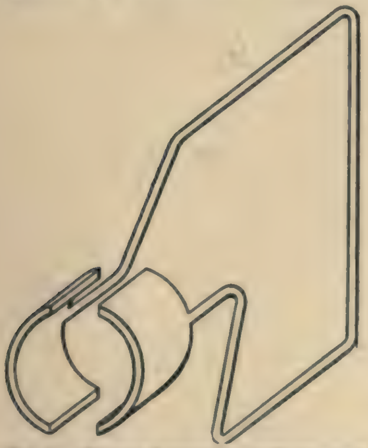


Fig. 21. Simple Commutator Connected to Loop with Single Turn.

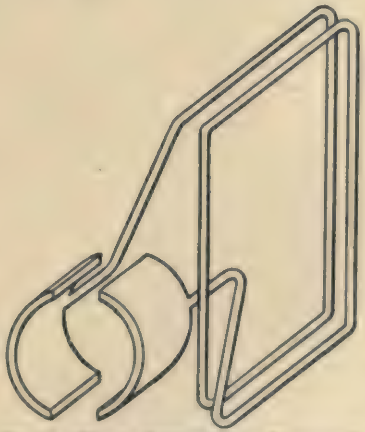


Fig. 22. Simple Commutator Connected to Loop with Double Turn.

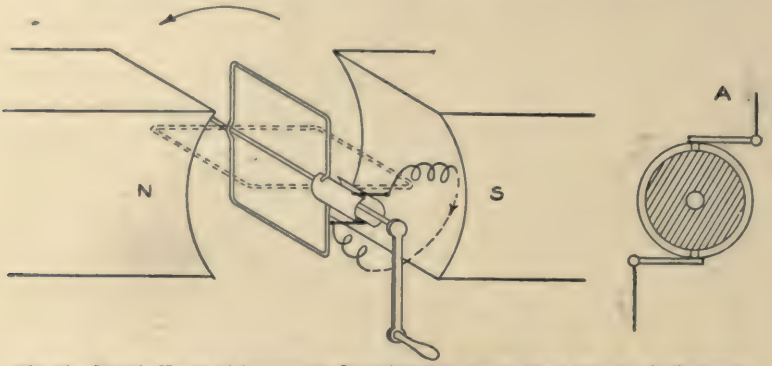


Fig. 23. Simple Form of Generator, Showing Arrangement of Brushes in Contact with Commutator to Give Unidirectional Current in External Circuit.

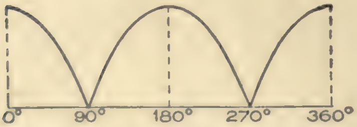


Fig. 24. Curve of Commutated Current.

In its simplest form, a commutator consists of a metallic tube slit longitudinally into two equal parts and mounted on a cylinder of insulating material, each half being connected to one terminal of a loop as indicated in Fig. 21. Fig. 22 shows a similar arrangement, except that the loop has two turns instead of one. Against this commutator, at diametrically opposite points, press a pair of metallic springs or brushes which lead the current due to the generated e. m. f. to the external circuit. If, as in Fig. 23, these brushes are so set that each half of the split tube moves out of contact with one brush and into contact with the other brush at the instant when the loop is passing through the positions where the time rate of cutting is minimum (as indicated in the enlarged end view of commutator shown at *A*), the alternating e. m. f. generated will produce in the external circuit a rectified, commutated, or unidirectional current. That is, the current in the external circuit will flow in one direction. If this external current be plotted, it will be of the pulsating character shown in Fig. 24. This explanation need not be changed, if, for a single loop, we substitute a coil wound on an iron ring as in Fig. 25. The effect of this is to increase the generated e. m. f. by increasing the number of times the electrical circuit cuts the flux. Now, referring again to Fig. 21, suppose, instead of one coil as there shown, we have two coils mounted side by side and connected in parallel to the commutator segments, we shall then obtain the elementary conditions shown in Fig. 26. If, then—similarly to the arrangement developed in Fig. 25—we place an exactly similar coil at the opposite side of the ring, as in Fig. 27, we see that when its terminals are connected to the same two half-rings as the first, the two coils are in parallel, and though the voltage generated by revolving this winding with two coils is no greater than with one coil, the current-carrying capacity of the resultant winding is evidently doubled.

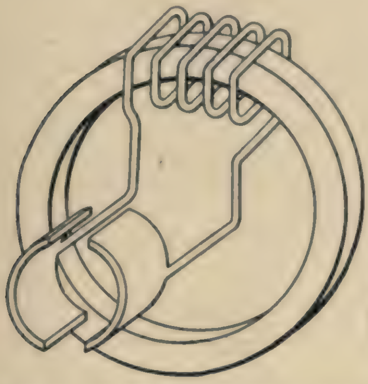


Fig. 25. Simple Ring Armature with One Coil.

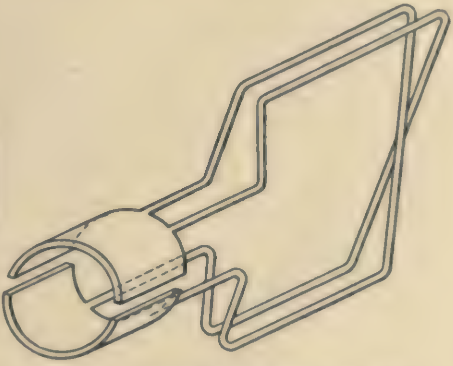


Fig. 26. Simple Loop Armature with Two Coils in Parallel.

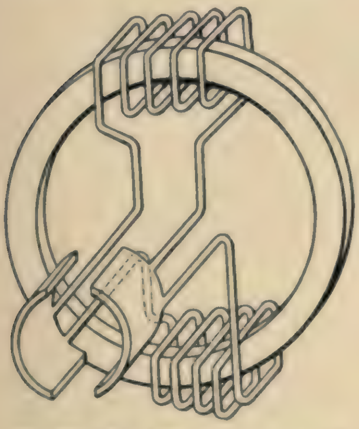


Fig. 27. Simple Ring Armature with Two Coils in Parallel.

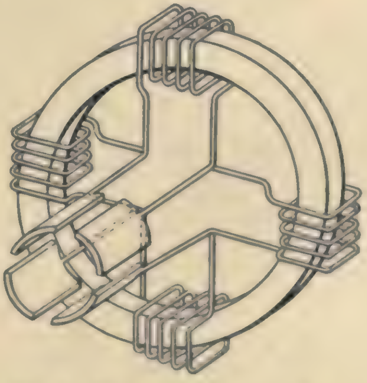


Fig. 28. Four-Part Ring Armature (Closed Coil).

The current obtained, however, from this arrangement has the disadvantage of being pulsating, as already shown. To give continuity to the external current we must multiply the number of generating coils, and also the number of commutator segments, arranging the coils around the armature so that one set will come into action before the other set goes out. If, then, we place upon the iron ring two additional sets of coils at right angles with the first set, as in Fig. 28, one set will be in the position of maximum activity when the other is in the position of least action; and Fig. 29 will represent the resulting external e. m. f. and current, which, although continuous (*i.e.*, never becoming zero), is not quite steady, having four slight undulations per revolution. By increasing the number of coils and commutator segments to a hundred or more, an external current can be obtained in which no undulations can be detected except by the telephone.

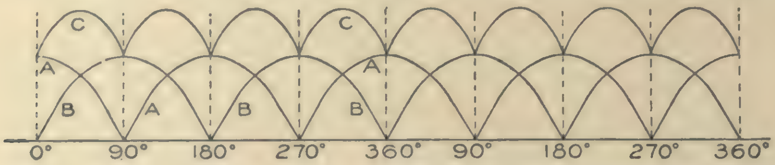


Fig. 29. Curve of E. M. F. and Current Generated by Armature Arrangement of Fig. 28.

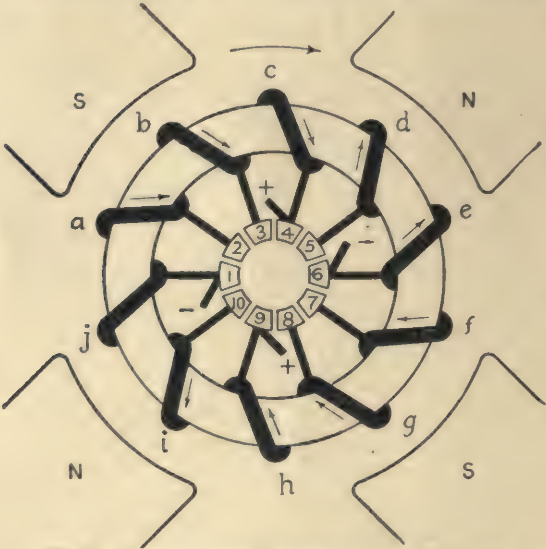


Fig. 30. Diagrammatic Representation of Gramme Ring Winding.

On examination of the winding represented in Fig. 28, it is apparent that the four coils are wound in series, the end of the first being connected to the beginning of the second, and so on, the end of the fourth being finally connected to the beginning of the first—the whole of the winding constituting, therefore, a single, closed coil. Also, it may be noted that the beginning of one coil and the end of preceding one are connected to the same commutator bar. In the practice the commutator is usually made up of a number of parallel bars of copper set around on, and separated from each other by, insulating material; and the armature is made up of a number of sections as in Fig. 30, which represents a Gramme ring winding. This, and other windings, will be treated more fully later.

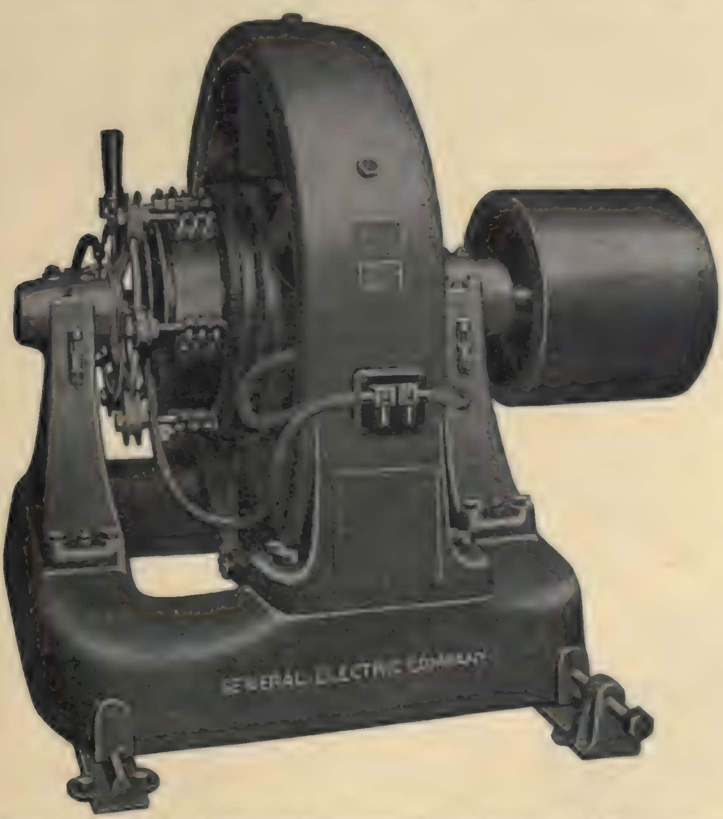


Fig. 31. Typical 6-Pole Belt-Driven Generator, Showing Armature, Field-Magnets, Commutator, and Brushes.

Organs of Continuous-Current Dynamos. We have seen that the dynamo in its simplest form consists of two main portions—an *armature*, which in revolving in a magnetic field generates an e. m. f.

in the conductors wound upon it; and a *field-magnet*, whose function it is to provide a flux for the conductors to cut as they revolve. These two parts are always present in all generators, whether for continuous current or for alternating current; and they are easily distinguished (Fig. 31). In almost all continuous-current machines, the field-magnet is a comparatively simple electromagnet which remains stationary; the armature, however, is more complex and usually rotates. In addition, we have seen that continuous-current machines require a commutator, while alternating-current machines are provided with *collecting* or *slip rings*. In either case, brushes are required to connect the revolving commutator or collector rings to the external circuit.

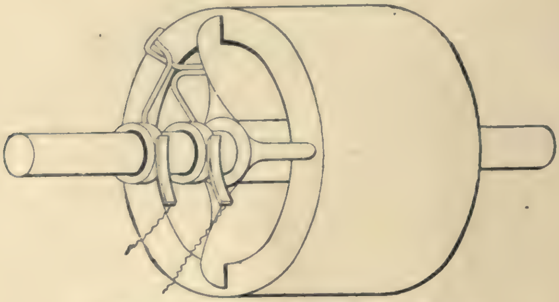


Fig. 32. Armature of Gramme Ring Type.

In continuous-current machines the field-magnet, being usually stationary, is combined with the bearings and bed-plate to form the frame of the machine. Similarly, the armature and commutator are supported by a spider and shaft, which rotate in the bearings attached to the frame. The complete machine comprises, in addition, various other mechanical parts taken up in detail later.

Armatures. Any electrical conductor—as, for example, a simple coil of wire—revolving in a magnetic field so as to cut the flux, would act as an armature and tend to have an e. m. f. generated in it. In order to obtain a practically steady direct current, together with maximum effect for a given amount of material, and to secure compactness, convenience of working, and other practical conditions, armatures have resolved themselves into the following types, although, theoretically, any figure of revolution around which coils are placed symmetrically, would answer:

(1) *Ring armatures*, in which the coils are grouped upon a ring core of iron whose axis of symmetry is also its axis of rotation.

(2) *Drum armatures*, in which the coils are wound longitudinally over the surface of a drum or cylindrical iron core.

(3) *Pole armatures*, in which the conductors are wound around radial iron cores projecting outward from a central hub.

(4) *Disc armatures*, in which the conductors are arranged in the form of a flat disc the plane of which is perpendicular to the axis of rotation, and usually not comprising an iron core.

The *ring armature* was first employed by Pacinotti in 1860, and described by him in 1865; but it is commonly known by the name of *Gramme*, the French electrician, who reintroduced it in 1870. Gramme wound the coils around the entire surface of the annular core, which he made of varnished iron wire in order to reduce the wasteful effects of eddy-currents; while Pacinotti had the coils wound between projecting teeth upon an iron ring. In ring armatures, the parts of the copper winding which pass through the interior of the ring do not cut any flux, and so are inoperative unless there are pole-pieces of the field-magnet projecting internally, which is not usually the case in practice.* Hence the ring type of winding offers a certain amount of wasteful resistance, which, however, can be made small compared with the resistance of the external circuit. Fig. 32 represents an armature of the Gramme ring type as generally used, although some machines are so designed as to have the outside of the ring act as a commutator, the current being collected directly from the winding by brushes which trail on the periphery of the ring, the inner parts of the conductors cutting the flux. Fig. 33 shows a completely wound Gramme ring armature.

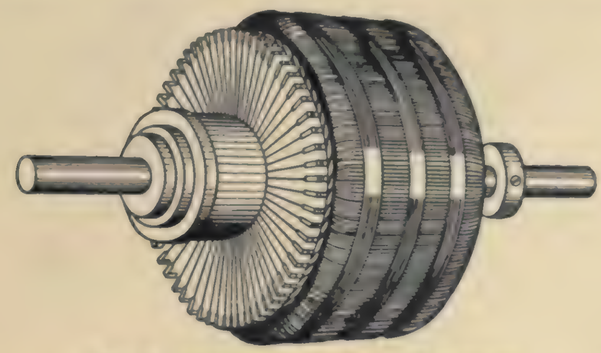


Fig. 33. Ring Armature of Gramme Dynamo.

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* In case of magnetic leakage through the opening in the ring core, the internal parts of the winding would produce an e. m. f. in the opposite direction to that generated by the outer sections, thus decreasing the effective voltage.

Drum armatures were introduced by Siemens, who wound cores of iron wire upon a frame of non-magnetic material. In their complete form, they were first brought out in 1871 by Von Hefner Alteneck, and improved later by Weston and others. As seen from Fig. 34, this type is even simpler than the ring, and consists in placing the elementary loop before described upon a supporting cylinder of magnetic material, so as to reduce the magnetic reluctance of the gap between the two faces of the field-magnet poles. This type of armature is almost exclusively used for continuous-current machines of to-day. In Fig. 35 is shown a partly-wound drum armature.

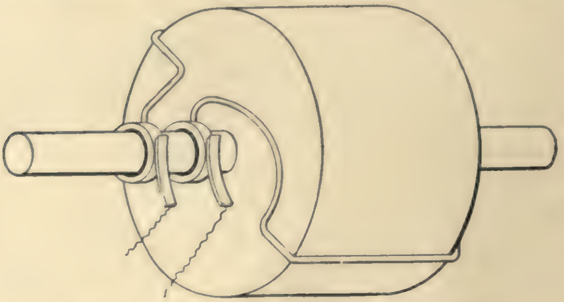
Fig. 34. Illustrating Method of Drum Winding.

Pole armatures—those having the coils wound upon projecting poles—were devised by Allan, Lontin, Weston, and others. They were used in Lontin's machines, as shown diagrammatically in Fig. 36. Owing, however, to the great self-induction thus introduced into each section of the winding, and the consequent sparking at the commutator, these machines were not successful. Pole armatures are to some extent used in alternating-current generators.

Disc armatures, illustrated in Fig. 37, have never been very widely used. The interesting feature of this type is the fact that there is no necessity for magnetic conducting material between the two faces of the field-magnet.

Armature Cores. The function of the armature core is two-fold: it supports the generating conductors, and carries the flux from one face of the field-magnet to the other face. On account of its high permeability and its great strength, iron is by far the best material for armature cores. We have seen, however, that when a mass of iron (or other conductor) is rotated in a magnetic field, wasteful eddy currents are set up in the mass. In order to reduce them as much as possible, it has become the practice to build up armature cores of thin soft iron or mild steel discs, insulated from each other by varnish, rust, or paper. These discs are arranged to have their planes parallel to the direction of the flux and perpendicular to the flow of eddy-currents. Solid cores of metal should on no account be used in any armature.

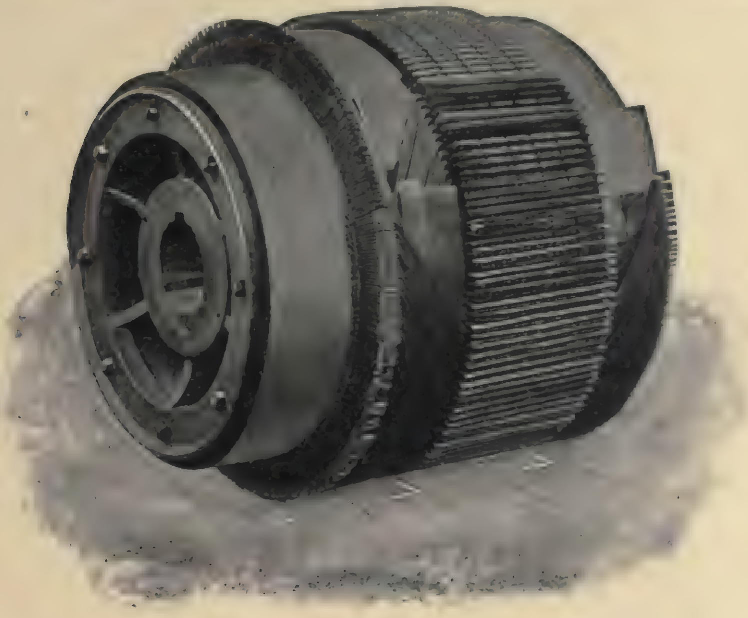

Fig. 35. Partly-Wound Drum Armature.

Field-Magnet Excitation. In order to generate an e. m. f. in the armature conductors, they must cut a flux. This flux is supplied by a magnet, and may be excited therein by five simple methods. These methods may be grouped under two headings, according to whether the armature of the machine furnishes the magnetizing current or m. m. f. required, or whether it is provided from some other source.

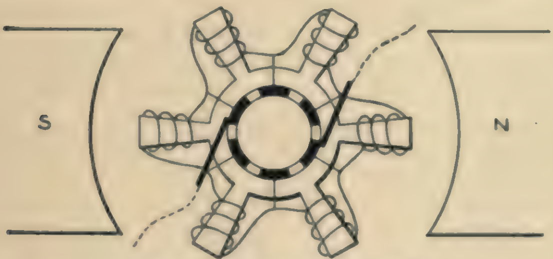

Fig. 36. Armature of the Pole Type.

(1) *Magneto-Machine.* In this type of generator, historically the first, the flux was provided by a permanent magnet as shown diagrammatically in Fig. 38. This method has the disadvantage of requiring a much bulkier machine in comparison with the methods to be described later, since permanent magnetism cannot be maintained at the high flux-density which may be produced by an exciting coil. It has, however, the advantages of simplicity and constancy, but is used only in the smallest of generators employed for example, to furnish current for ringing bells, for ignition in internal-combustion engines, etc.

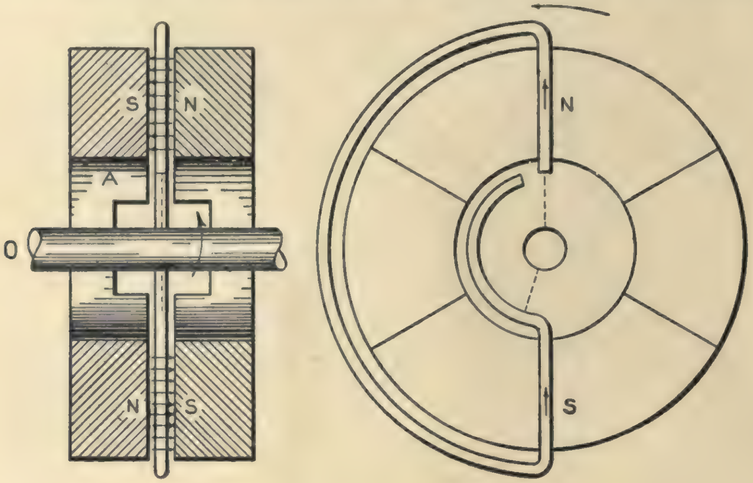

Fig. 37. Armature of Disc Type with Two Inductors in Series.

(2) *Separately-Excited Generator.* The next step was to excite the field-magnets by means of a coil fed from some source of electrical energy other than the generator itself. This method, outlined in Fig. 39, produces the same results as the magneto method, without the disadvantage of great bulk. It requires, however, a separate machine or battery for excitation purposes solely, and the method is not employed in continuous-current practice, except where many machines are in operation, or where their terminal voltage exceeds 800 volts. It is largely employed in exciting the fields of alternating-current generators, since an alternating current will not produce a unidirectional magnetic field.

In either of the methods just mentioned, the e. m. f. of the machine may be governed in three ways—namely, by (*a*) altering the speed of rotation of the armature; (*b*) by varying the number of effective conductors by moving the brushes; and (*c*) by changing the magnetic flux through the armature. The latter is altered in the case of magneto-machines by shunting the flux away from the armature through an auxiliary piece of iron. In the case of separately excited machines, the flux is varied by regulating the exciting current or the number of turns of the solenoid.

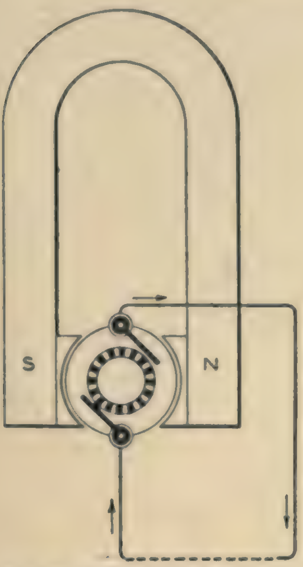

Fig. 38. Diagrammatic Representation of Magneto-Generator.

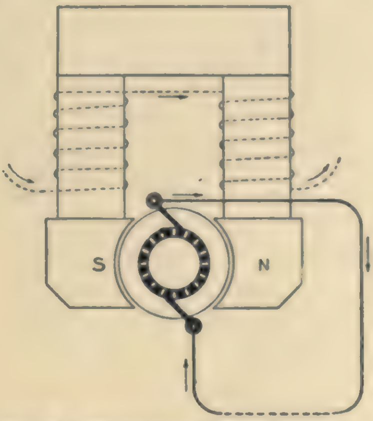

Fig. 39. Diagrammatic Representation of Separately-Excited Generator.

Generators of the continuous-current type may be made *self-exciting* by either of four methods. The whole current supplied by the machine to the external circuit may be passed through the solenoid, or a part of the total current may be passed through the field-winding; or two field-windings may be employed, one traversed by the load current and the other by the shunt current; or, finally, the field-exciting current may be produced by an e. m. f. generated by a separate winding on the armature of the generator.

(3) *Series Dynamo.* The series continuous-current generator outlined in Fig. 40 has but one circuit. It has, however, the disadvantage of not starting to generate until a certain speed has been reached or unless the resistance in the external circuit is below a certain

limit. It also is liable to become reversed in polarity, thus unfitting it for electrolytic work. Any increase in its external resistance, at a given speed, diminishes the current stream that excites the magnetic circuit, thereby lowering the e. m. f. Conversely, reduction of external resistance tends to increase the e. m. f. of the machine until the *IR* drop and the armature reaction become so large that the available voltage falls more rapidly than the field stream increases. The only series generators actually employed supply *arc lamps in series,* and are provided with automatic regulators to maintain constant current; hence the external voltage and power are directly proportional to the external resistance.

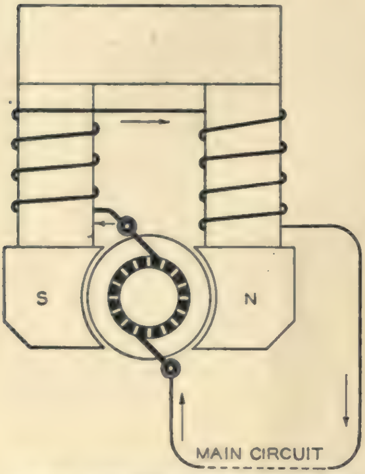

Fig. 40. Diagrammatic Representation of Series Continuous-Current Generator.

(4) *Shunt Dynamo.* In the shunt-wound generator, Fig. 41, only a small part of the current in the armature passes through the field winding. The field-exciting circuit F_{sh} has, therefore, a relatively high resistance compared with that of the external circuit. This machine is tolerably self-regulating within certain limits, when properly designed; but if overloaded, its internal actions are such as to reduce its generated e. m. f. to zero. Its polarity never reverses of itself; and although it is a trifle more expensive to buy than the corresponding series machine, its self-regulating properties more than overbalance this. The amount of energy required for excitation in either series or shunt field-windings for identical machines, is precisely the same, since to produce a given flux (as shown in the discussion of the magnetic circuit) demands a definite number of *ampere-turns.* In the series machine, the *turns* of wire are few in number, while the current in *amperes* is relatively large. In the shunt type, the reverse is the case.

(5) *Separate-Circuit, Self-Exciting Generator.* The third type of self-exciting machine is that in which the field circuit is supplied by only part of the armature, or by separate windings on the armature,

as represented in Fig. 42. This arrangement is adopted for A. C. generators and for D. C. machines in which the e. m. f. generated is over 800 volts, since it is undesirable to apply such voltage to field excitation. In effect, however, it is almost the same as the separately excited machine (No. 2, above).

Generator Regulation. In all the simple methods of field excitation just described, the e. m. f. generated by the dynamo varied more or less with load. If the load were constant (*i.e.*, if the same number of lamps were being supplied all the time), the generator could be designed to give a predetermined terminal voltage. But under usual working conditions, the load connected to an electric generator—such as lamps, motors, or other devices—is continually changing, so that it is essential to provide some device whereby its e. m. f. may be varied to suit the varying load. The generated e. m. f. is the sum of the terminal voltage and that lost in overcoming internal reactions, the latter quantity varying with load. As stated previously, there are three methods for regulating the generated e. m. f. of the dynamo—namely, by varying the speed of rotation of the armature, by varying the magnetic flux, and by changing the number of effective or active armature conductors.* Of these three possible methods, however, the only one utilized is that of varying the magnetic flux, it having been found more convenient to regulate the prime mover for constant speed than for speed increasing with load, while the method of changing the effective armature conductors by shifting the brushes is conducive to bad sparking at the commutator. As has been noted, the most advantageous way to vary the magnetic flux is to vary the current in the energizing coils.

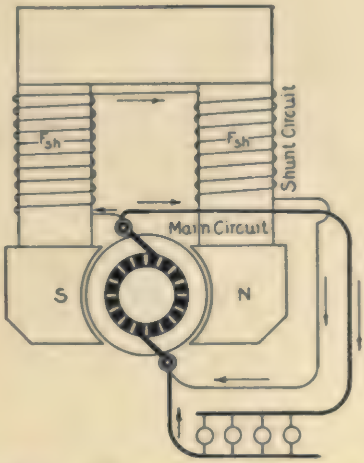

Fig. 41. Diagrammatic Representation of Shunt-Wound Generator.

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*The expression "active armature conductors" refers to those conductors which are actually cutting flux and generating an e. m. f. at any instant.

Since the current in the field-exciting coils is dependent upon the e. m. f. impressed at their terminals and upon their ohmic resistance, we can increase the magnetic flux by decreasing the resistance of the field-exciting circuit or by increasing the terminal voltage impressed there. Also, the flux may be made to increase with load, by passing the external current of the generator through a few turns of thick wire, called *series turns* or *compounding turns,* placed upon the field-cores. The first method is usually non-automatic, and is applicable to shunt and separately excited machines; the second is applicable to separately excited machines; and the third, to both types; and a generator thus equipped is called a *compound generator.*

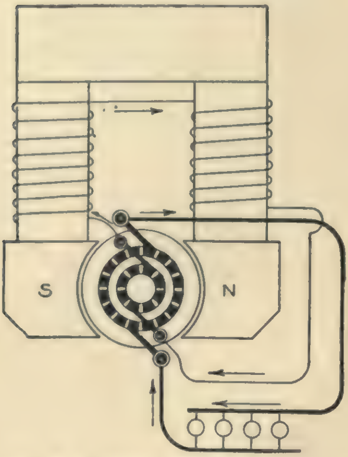
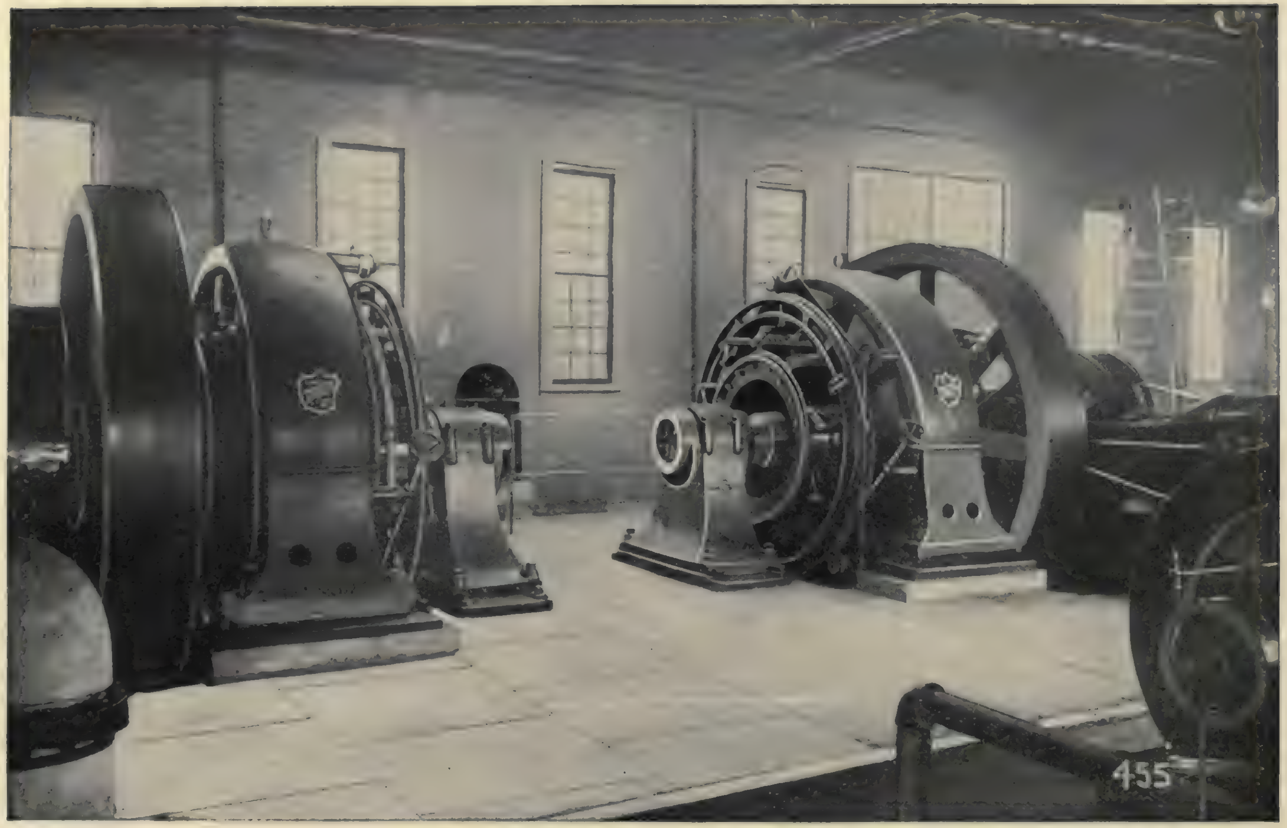


Fig. 42. Diagrammatic Representation of a Separate-Circuit, Self-Exciting Generator.

Methods of Compounding. (1) *Separate and Series* (Deprez). The connections are shown diagrammatically in Fig. 43, a separate source of e. m. f. being used to produce the initial and constant excitation, while the external current of the machine is led through a series winding, thus compensating for the internal drop of the generator to any desired degree, even *increasing* the terminal voltage with load if desired.

(2) *Shunt and Series.* By far the most widely used of all compounding schemes, however, is the one in which series turns are added to the plain shunt winding, as illustrated diagrammatically in Fig. 44. By properly proportioning the ampere-turns in the shunt and series coils, the terminal voltage-load curve may be made to take any desired form. For instance, it may be made constant, increasing or decreasing throughout the rated load range of the machine. This arrangement will be considered in detail later on.

(3) *Booster Method.* This consists essentially of an auxiliary generator in series with the main machine, the e. m. f. of the former being low; and since its field winding is in series with the external circuit, it will automatically regulate the voltage of the combination in accordance with the load



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(4) *Miscellaneous Methods.* If the generator armature be wound according to a special scheme devised by Sayers,* the field excitation may be produced by a simple shunt winding, and a compounding effect produced by giving the brushes a backward lead. Other methods of compounding may be found in S. P. Thompson's "Dynamo-Electric-Machinery."

Actions in the Armature. Thus far we have considered the armature and the field of the generator separately, assuming that the former did not affect the latter. It is found, however, that when the armature of a generator or motor is carrying current, its action is not the same as when it carries no current, owing to the distortion of the field flux by the magnetization of the armature. In order to study the effects produced, we shall consider a dynamo of the simple bipolar type (Fig. 45) with a ring armature, when the machine is operating without and under load.

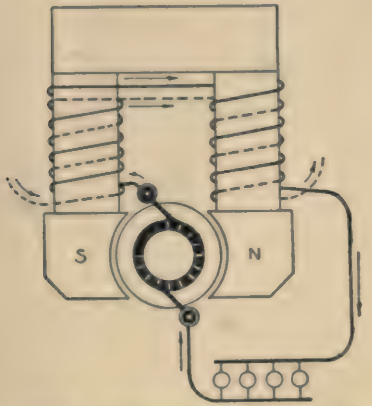

Fig. 43. Separate and Series Method of Compounding.

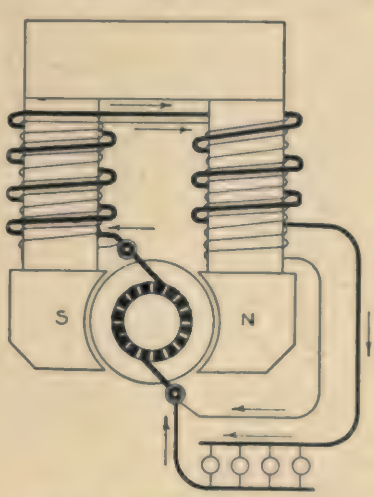

Fig. 44. Shunt and Series Method of Compounding.

Suppose the armature to be rotating clockwise, when viewed from the commutator end, and that the north pole of the field-magnet is at the right of the armature, the south pole being on the left, as in Fig. 46. The flux will then pass from right to left through the armature; and the e. m. f. generated in the moving conductors of the armature is, in accordance with Maxwell's law, as follows:

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* See E. Arnold's *Gleichstrommaschine* (Erster Band, Berlin, 1902), pages 417, 449, *et seq.*

In all the conductors which are ascending, the generated e. m. f. is directed toward the observer; while in all the descending conductors, the generated e. m. f. is directed away from the observer. If the circuit through the armature is closed, the generated e. m. f. will produce a current flowing in the same direction; and in Fig. 46 the current-flow in the armature is toward the top and away from the bottom on both sides. This result is obtained when the armature is wound right-handedly, being the opposite if the winding is left-handed. With a drum-wound armature, the result is the same; but the diagram is more complex on account of the end connections.

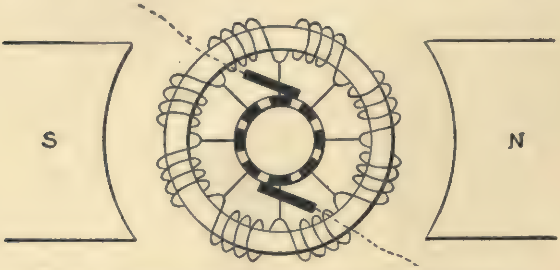

Fig. 45. Diagrammatic Representation of Simple Ring Armature.

It will be noted that the path of the current is from brush to brush, through each of the armature coils, without going to the commutator except where it passes out to or returns from the external circuit. We have seen, however, in the ideal dynamo, that the e. m. f. generated in an armature coil is proportional to the time rate at which the flux is cut. In the case illustrated in Fig. 47, no two armature coils are cutting the same amount of flux at any given instant, so that the voltage generated in each coil depends upon its position in the field. Since one-half of the coils are connected in series between the brushes, the total difference of potential (p. d.) measured at the latter will at any instant be the sum of the instantaneous e. m. f.'s generated in the individual coils.

If the field were uniform, it is plain that the flux cut at a given instant by any one coil would be proportional to the sine of the angle which it makes with the direction of the field at that instant; so that if we plot the values of these instantaneous potentials as ordinates, and the corresponding angles as abscissæ, we obtain Fig. 47.

Thus it is seen that the p. d. obtained at the brushes may be compared to that obtained at the terminals of a battery connected as shown in Fig. 48, each cell representing an armature coil and being supposed to supply an e. m. f. equal to that generated by the coil it replaces. The terminal voltage will then be obtained by adding all these potentials between the 0° and the 180° positions in Fig. 47, or integrating the voltage curve between these limits, the negative part being exactly equal to the positive half if the dynamo is symmetrical. The sum thus obtained grows slowly at first, then rapidly, and slowly again as it reaches its highest value, repeating this program in the other half-circumference. These facts are shown at reduced scale in Fig. 49. In the actual dynamo, this integration is effected because the coils are connected in series; and it is possible to demonstrate this experimentally.

Exploration of Potentials around a Commutator. Several more or less simple ways of showing the distribution of the generated e. m. f. around the commutator of a dynamo, have been suggested,* but only one, Mordey's method, will be taken up here. It consists in connecting one terminal of a voltmeter, preferably an electrostatic one, to one brush of the machine, and the other terminal to a small pilot brush *b* (Fig. 50), which can be moved from point to point around the commutator. The armature of the generator is then rotated at its rated r. p. m. (revolutions per minute); and, starting at the brush *N*, *b* is placed in successive positions around the commutator, the voltmeter reading in each position being noted, together with the corresponding angular situation of *b*.

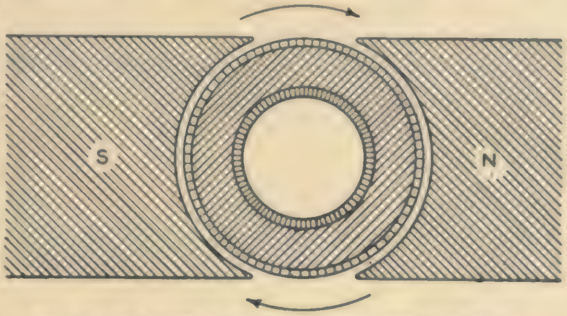

Fig. 46. End View of Ring Armature in Bipolar Field.

These results, plotted with the voltage readings as ordinates and the corresponding values of angular situations of *b* as abscissæ, are as represented in Fig. 51, when the armature is carrying no current. The curve so obtained is not usually a true sine curve in commercial machines, because the magnetic field in which the armature rotates is not uniform. Also, we shall see later that when the armature carries a current, its presence causes a further distortion in the distribution of the flux. Furthermore, the setting of the brushes or an injudicious shaping of the pole-pieces will cause irregularities to be present in this curve, examples of which have been given by Von Gaisberg[*], Kohlrausch[**], M. E. Thomson[***], Ryan[†], and Shephardson[††].

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*See S. P. Thompson's "Dynamo-Electric Machinery," Vol. I. (N. Y., 1904), page 204.

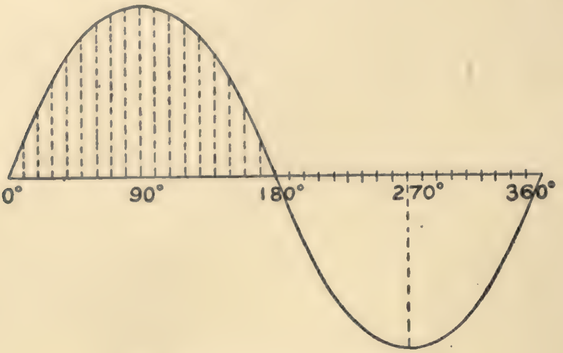

Fig. 47. Curve of Induced E. M. F.

Reactions in the Armature. This leads us to consider the reactions of the armature when the generator is operating, which are manifested in many ways, the most important being:

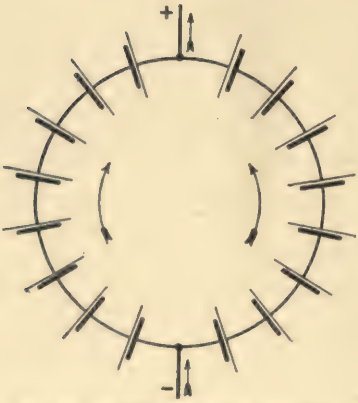

Fig. 48. Battery Analogy of Simple Dynamo.

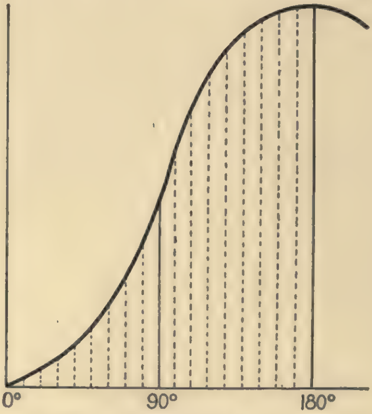

Fig. 49. Integrated Curve of Potentials.

(1) A tendency to *cross-magnetize* the armature.
(2) A proneness to spark at the brushes.

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[*] *Elektrotechnische Zeitschrift*, vii 67, Feb. 1886.
[**] *Centralblatt für Elektrotechnik*, ix 419. 1887.
[***] "Electrical World," xvii 392, 1891.
[†] Trans. Amer. Inst. Elec. Engrs., vii 3, 1890.
[††] "American Electrician," x 458, 1898.

(3) Variation of the neutral point of the armature with the amount of current.

(4) The consequent necessity of shifting the brushes.

(5) A resultant tendency to demagnetize the armature.

(6) Losses due to eddy currents in the pole-pieces, armature core, and coils.

(7) A resulting difference between the input and output.

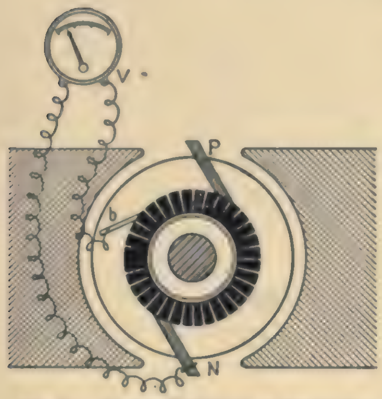

Fig. 50. Mordey's Method of Exploring Potentials around Commutator.

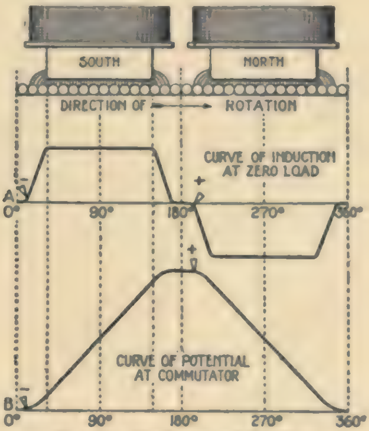

Fig. 51. Undistorted Field.

As these reactions have much effect upon the operation of the commercial machine, they will be considered in detail.

Cross-Magnetizing Effect of Armature Current. We have seen from Fig. 48 and the accompanying text, that the armature of a generator may be likened to a combination of voltaic cells; but the armature carrying current manifests a magnetic effect absent in the latter.

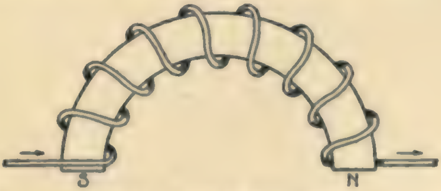

Fig. 52. Poles on Half-Ring.

If we consider the solenoid of page 4 to be bent around so as to form a semicircular ring, and to have inserted into it an iron core of the same form, one end of this core would act as a north pole, and the other end as a south pole, when current circulates in the winding (Fig. 52). By taking an exactly similar semicircular ring and placing the two together so that their north poles and the south poles are respectively coincident, we are able to reproduce the magnetic effect of current flowing in the armature. That is, when the generator supplies energy to the external circuit, the armature has poles produced in it corresponding to the brushes—namely, where the current enters and leaves the winding. This magnetization of a simple Gramme ring armature (Fig. 53) is indicated in Fig. 54, the general direction of the flux being through the armature core along both paths from *a* and *b* to *n* and *s*, where it emerges into air, forming respectively the poles of the armature. The main portion of this flux returns outside the ring, while a small portion passes across the interior. This latter portion is extremely small in commercial machines, on account of the presence of large masses of iron in the pole-pieces which are outside.

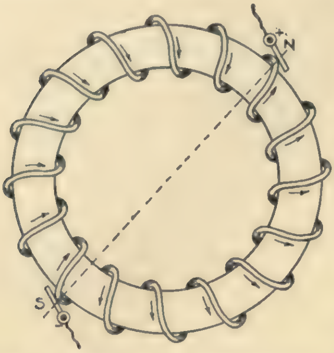

Fig. 53. Circulation of Current around Ring Armature.

The cross-magnetization of the armature produces a distortion of the flux in it; but this would have small effect upon the e. m. f. if the line of commutation did not also change with the armature current. This change necessitates the moving of the brushes; and then the armature not only produces a cross-magnetizing effect, but also has a demagnetizing tendency. It is this latter which diminishes the generated e. m. f.

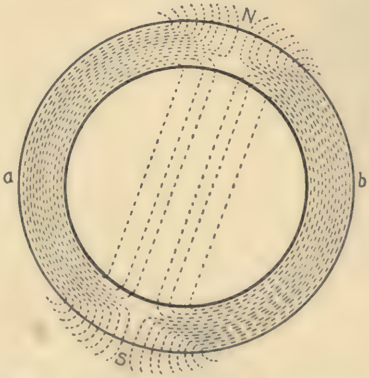

Fig. 54. Magnetization Due to Armature Current.

In order to study the result, let us suppose the simple bipolar dynamo of Fig. 45 to be arranged so that current may be passed through its field windings, its armature when rotating, or through both. When the field alone is excited, the flux distribution will be substantially as indicated in Fig. 55—that is, quite uniform in the pole-pieces, air-gaps, and armature. If, now, the field-exciting circuit be opened, and if a current be supplied to the rotating armature equal to its rated load current, the flux distribution shown in Fig. 56 will exist. By combining these two conditions of the flux, there is produced the distortion shown in Fig. 57, which is the resultant flux distribution in the generating portion of the machine. The magnetism is distorted in the direction of rotation, as if the armature tended to draw after it the flux issuing from the field-poles. But this is not the physical fact, because we find that in electric motors the flux is distorted in a direction *opposite* to that of the rotation of the armature. In fact, the flux-distribution is the same whether the armature turns one way or the other, or not at all. On account of this flux distortion, brushes must be set, not midway between the field-poles, but, in the case of generators, somewhat ahead of this line of symmetry. Consequently the armature m. m. f. will be oblique to that due to the field-magnet, and a further distortion will result.

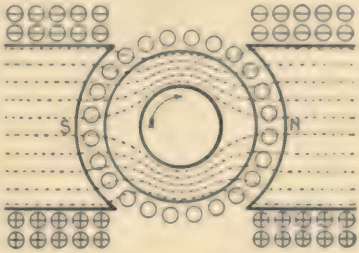

Fig. 55. Flux Due to Field Alone.

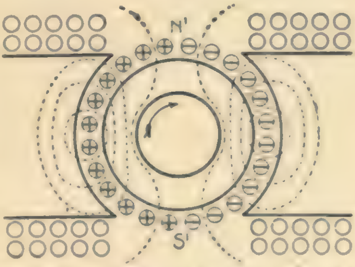

Fig. 56. Flux Due to Armature Alone.

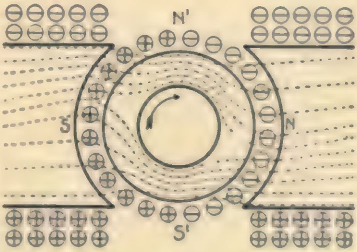

Fig. 57. Flux Due to Field and Armature.

These relations are shown vectorially in Fig. 58, the line OF representing in direction and magnitude the flux due to the field-magnet, and the line OA' the direction and magnitude of the flux set up by the armature current with the brushes in the line of symmetry or vertical position. In this case, OR' represents the resultant flux in value and direction, and the brushes should be shifted to the line OA'', perpendicular to OR'. The armature component of the flux also shifts to this direction, but with unchanged magnitude because the ampere-turns and other relations of the magnetic circuit are not varied. This will produce a new resultant OR'', and the brushes should be shifted until the line of commutation OA is approximately perpendicular to OR, the final flux vector. These conditions are also represented in Fig. 59, OF being the field-magnet flux, OA the armature flux with the brushes shifted, and OR the resultant with the main line of the flux (PQ) as an extension of it.

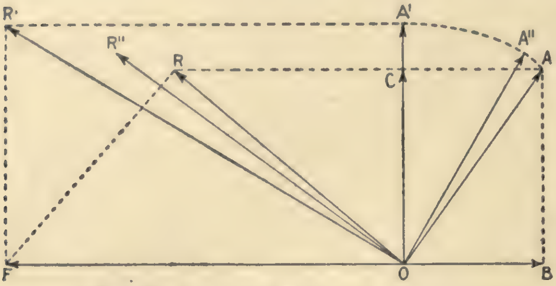

Fig. 58. Magnetic Reactions in Armature.

In the case of drum-wound armatures, the phenomenon is similar but not so easily traced. In consequence of the overlapping of the end-connections, the magnetizing effects of some of the coils are neutralized, and as a result the production of poles is not so marked. Neither can there be any internal field. As a matter of fact, drum-wound armatures are not troubled to the same extent with induction effects as are ring-wound ones. With these exceptions, however, the facts here considered apply equally to drum-wound and ring-wound armatures.

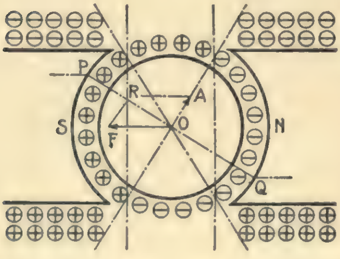

Fig. 59. Back and Cross Ampere-Turns.

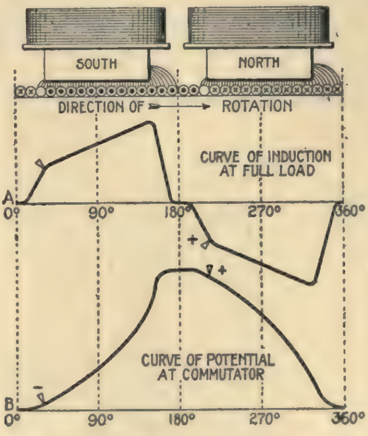

Fig. 60. Curve of Armature Distortion.

The distortion of the flux through the armature also produces a distortion in the wave of induction, as may be shown by exploring the potential differences around a commutator by Mordey's method, when the machine is carrying its rated load. Such a curve is shown in Fig. 60.

Sparking at the Commutator. On page 20 we have seen that the rotation of the armature in the field of the machine generates alternating currents in the conductors. A consideration of Fig. 57 shows that all the current flows toward the spectator in the conductors which are rising, and away from the observer in all the descending conductors, the brushes in this case being supposed present at N' and S'. Thus, when a coil passes under one of the brushes, the direction of the current in that coil is *reversed*. Owing to the fact that even a single armature coil possesses some self-induction, the current cannot change instantaneously; that is, a certain definite interval of time is required, dependent upon the self-inductive property of the armature coil, as well as upon its resistance. During this interval, and until the whole current can take the new path through the coil, a portion of the current continues to flow from the receding commutator bar, through the air, to the brush, in the form of a spark. It is the interruption of this latter current, as the commutator bar leaves the brush, that produces the spark.

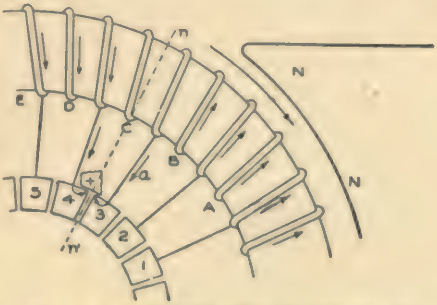

Fig. 61. Illustrating Requirements for Non-Sparking Condition of Commutation.

Commutation. In order to understand exactly what happens when a current is commutated, let us consider what takes place in one section of an armature winding, and at the two commutator bars attached to the latter, when the bars pass under a brush.

Fig. 61 shows a portion of a ring-wound armature with its coils *A*, *B*, *C*, *D*, and *E* connected to segments 1, 2, 3, 4, and 5 of the commutator, and a positive brush just beyond the leading tip of one of the pole-pieces. The line *nn'* represents a line drawn in space so as to cut the commutator at a point where the voltage between the brush and the bars thus passed through is zero. The brush is assumed placed in this line.

Now, before any given section of the winding reaches the brush shown in the figure, a current will be flowing in it in the direction of the positive brush; and after the section has passed the brush, the current, although reversed in direction, is still flowing towards the brush.

The figure shows the instant at which coil C is short-circuited by the brush through the commutator bars 3 and 4; and it is during the brief interval of this short circuit that the current in coil C must be reduced to zero, reversed, and then built up again in order that there shall be no tendency for a spark to form between the brush and the bar 3 at the instant they part.

As to the establishment of a reversed current in section C while it is short-circuited by the brush, it must be remembered that this coil is at this instant supposed to be occupying a position such that there is no e. m. f. being generated in it; that is, it is in a neutral position. In coils to the immediate left and right of coil C, however, e. m. f.'s are being generated in such a direction as to cause the resulting current to flow *towards* the brush. If, therefore, we move the brush forward—that is, in the direction of rotation—from its present position in the neutral line, the section short-circuited by that brush will be placed in a region where a p. d. will be generated between its terminals in such a direction as to assist the reversed current above mentioned. Also, the greater the forward lead—that is, the further away from the neutral line in the direction of rotation the brush is moved—the greater will be the p. d. so generated; so that by trial, a position of the brush may be found where the condition of sparkless collection is fulfilled.

The use of high-resistance carbon brushes tends to cause a decrease to zero of the current existing in the sections before they reach the brush, since the latter forms part of the short circuit. Their use also aids the establishment of the reversed current in the short-circuited section, before the brush and segment part company. This is due mainly to the contact resistance between the brush and the commutator, as follows:

The current flowing across the contact area of the brush and leading segment under it (in the figure, segment 3), produces a drop of potential there, which is small on account of the large area of contact, at the instant depicted. A moment later the brush is making better contact with segment 4, and poorer contact with segment 3, so that the voltage drop across the contact area of the brush and 3 has risen above that of the brush and 4. Hence a current will tend to flow from segment 3 to segment 4, as a reverse current through C, being produced by the difference of potential between them. This state is comparable to that of the ordinary potentiometer, where a "drop" acts as an e. m. f. in producing a current flow. The voltage resulting from this potential difference across the two contact areas mentioned, assists that tending to produce reversal.

Thus, as the commutator moves under the brush (assuming the latter to have a forward lead), the e. m. f. for reversal, the p. d. due to the varying contact area of the brush, and the resistance of the short-circuited coil, combine to reduce the current in the latter to zero, while the self-induction of the coil tends to prevent any change of the current in it.* This zero condition should occur when the areas of contact between the brush and the two (in this case) bars passing under it are equal. Then, when the segments leave this position, the p. d. between them will increase, thus assisting the direct e. m. f. (produced in the coil by the flux from the hindward pole-horn) in establishing a current in the coil in the reverse direction. Opposing this are the resistance and self-induction of the coil. With proper conditions, the various reactions mentioned may be so proportioned as to produce in the coil from which the short circuit is about to be removed, a current equal in amplitude and direction to that flowing towards it from the preceding coil. In the figure, coil

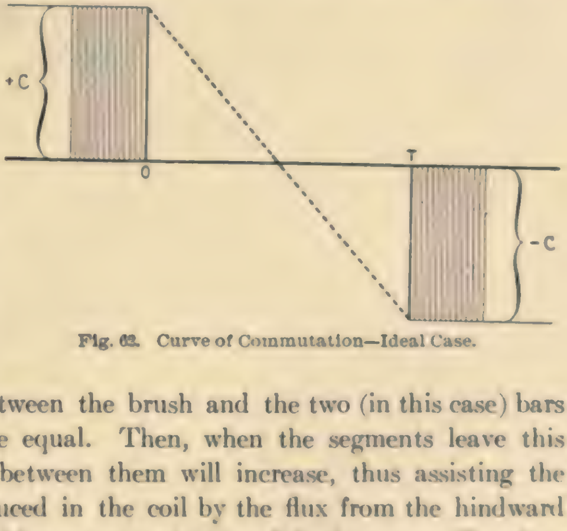

Fig. 62. Curve of Commutation—Ideal Case.

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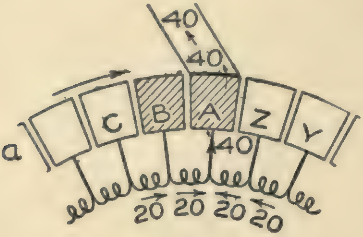
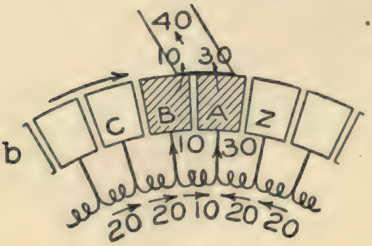
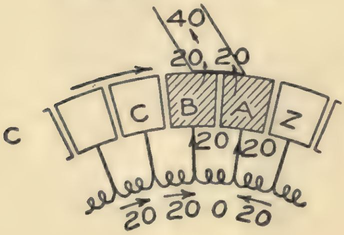
[*] See S. P. Thompson's "Elementary Lessons in Electricity and Magnetism." N. Y., 1903, pp. 466 *et seq.*



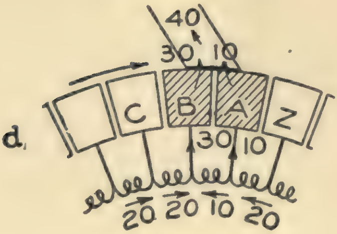
(*a*) Instant before Commencement of Commutation in Section *AB*.



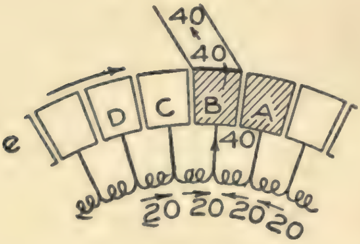
(*b*) End of First Quarter of Period of Commutation in Section *AB*.



(*c*) End of Second Quarter of Period of Commutation in Section *AB*.



(*d*) End of Third Quarter of Period of Commutation in Section *AB*.



(*e*) Commutation in the Section *AB* Completed.

Fig. 63. Process of Commutation.

C would be the one to have the short circuit removed; and *B*, the preceding coil. Then segment 3 will pass out of contact with the brush without a spark attempting to follow.

Resistance during Reversal. Let us assume that during commutation the brush contact resistance is inversely proportional to the area of contact. Then, in the ideal case, where the coils of the armature are devoid of resistance and inductance, the curve of commutation will be as shown in Fig. 62, *C* representing the value of the current to be commutated, *O* the instant when commutation commences, and *T* the period requisite for this action. Here the current gradually diminishes to zero at the middle of the commutation period, and reaches its negative maximum value at the end of the time *T*. This process is shown in detail in Fig. 63, the brush being wide enough to span one commutator bar.

In this case 20 amperes flow from either side of the armature to the brush, the latter leading away 40 amperes. If we suppose the brush area to be one square inch, then, when the commutator is in the position indicated by Fig. 63 (*b*), the area of contact of the segment *A* is reduced to $\frac{3}{4}$ square inch, while that of the segment *B* has become $\frac{1}{4}$ square inch, so that 10 amperes will flow into the brush from *B* and 30 amperes from *A*, the additional 10 amperes through the latter coming from the short-circuited coil. When the commutator has moved forward so that the area of contact of each brush is the same—that is, $\frac{1}{2}$ of a square inch—*A* and *B* will each pass 20 amperes to the brush from either side of the armature, the coil undergoing commutation carrying no current at this instant (see Fig. 63, *c*). At the end of the third quarter of the commutation period, the commutator has reached the position shown in Fig. 63 (*d*), the area of contact of segment *A* with the brush being $\frac{1}{4}$ of a square inch, while that of *B* is $\frac{3}{4}$ of a square inch. Hence *A* will contribute 10 amperes and *B* 30 amperes to the brush, the coil undergoing commutation now carrying a current in the direction reverse to that indicated in Fig. 63 (*b*), and in the same direction as the current in the coils on the right. At the end of the commutation period, the current in coil *A–B* has increased to the full value of that flowing in its right-hand neighbor; and when the brush and segment *A* part company no spark will result.

Fig. 62 shows the variation of the current during this period, if we neglect the resistance and inductance of the armature coils. It therefore remains to consider the effect of these reactions.

Commutation Curves. If the resistance of the armature coils be not negligible in comparison with the contact resistances, then the current collected will not be rigidly proportional to the areas of contact. For, suppose that in Fig. 63 (*b*) the contact resistance over *A* is 0.04 ohm, and that that over *B* is 0.12 ohm; then, if the resistance of one coil of the armature be taken at the exaggerated value of 0.01 ohm, 29.6 amperes will go through *A*, and 10.4 amperes will pass through *B*. In other words, the presence of resistance in the coils of the armature reduces the ratio of currents during the first half of the commutation period, and increases this ratio during the second half. This is shown graphically by the curved line in Fig. 64, the straight line indicating the ideal case.

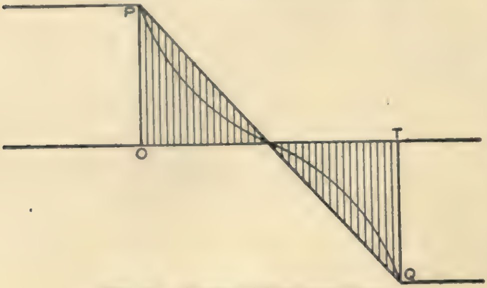


Fig. 64. Curve of Commutation.

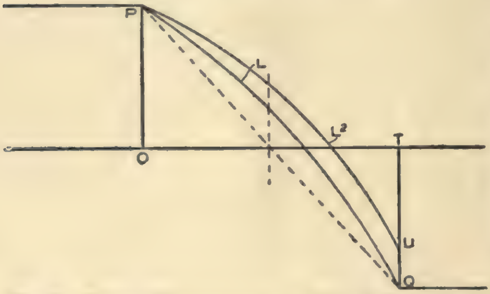


Fig. 65. Curve of Commutation, with Self-Induction.

The effect of self-induction, although not easily shown quantitatively, would modify the ideal current curve as indicated by PL^1Q in Fig. 65, PL^2U showing the result obtained with increased self-induction. Self-induction tends to retard any change in the current, so that the same is not completely reversed at the end of the commutation period. At the last instant, then, as the surface of contact between the segment *A* and the brush diminishes to zero, the contact resistance rises with extreme rapidity. The product of this resistance and the still uncommutated part of the current, will constitute a p. d. between the retreating segment *A* and the tip of the brush. This p. d., represented graphically by *QU* in Fig. 65, tends to set up a spark, and may be briefly called the *sparking* or *maintaining* e. m. f.

The resulting commutation curve for any machine is made up of these two effects, the quantity of each depending upon the design, and of some details at present obscure. Messrs. Everett and Peake[*] found experimentally that the curve had the form shown in Fig. 66. Curve *A* indicates the initial rise which may obtain at light loads, with an oval resultant at the negative end. *B* illustrates under-commutation with insufficient lead. *C* shows, with increased load, a rapid reversal at the beginning of the commutation period, but under-commutation toward the end. *D* represents a gradual fall of the current, which slackens toward the end.

Effect of Increasing Breadth of Brush. Increasing the breadth of the brush not only lengthens the period of commutation, but also permits commutation to start in one coil before the preceding coil has entirely passed through this stage.

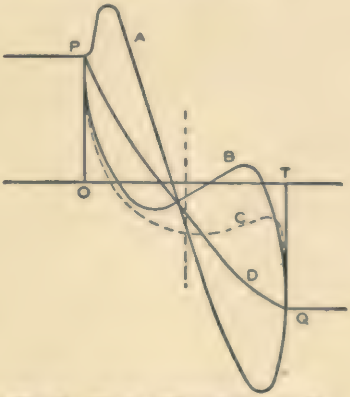


Fig. 66. Curve of Commutation Observed by Everett and Peake.

In Fig. 67, let us assume the brush to have an area of 3 square inches, and that it can completely cover two segments at one time, the current collected by the brush being 120 amperes. Then Fig. 67 (*a*) shows the state of affairs when the segments *A* and *Z* are under the brush. An instant later, the commutator, in moving clockwise, starts to uncover segment *Z* and to cover segment *B*, so that at the end of the first quarter of the period of commutation, the result will be as indicated in Fig. 67 (*b*), for the ideal case. Similarly, in Fig. 67, *c*, *d*, and *e* represent respectively the conditions at the end of the second, third, and fourth quarters of the commutation period, the direction of current and its magnitude in each coil being indicated by arrows and figures. We see from these that the conditions of Fig. 63 (page 44) obtain throughout, the current in the short-circuited coils being zero at the middle of the period of commutation; so that we may conclude that the act of commutation is not altered by increasing the width of the brush.

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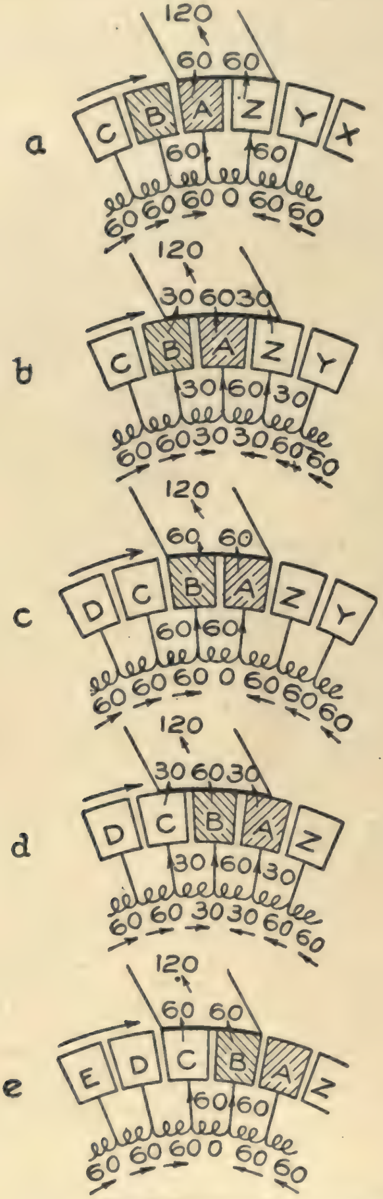
[*] See *Electrician*, London, Vol. 40, p. 461; Vol. 42, p. 338.



(*a*) Instant before Commencement of Commutation in Section *AB*

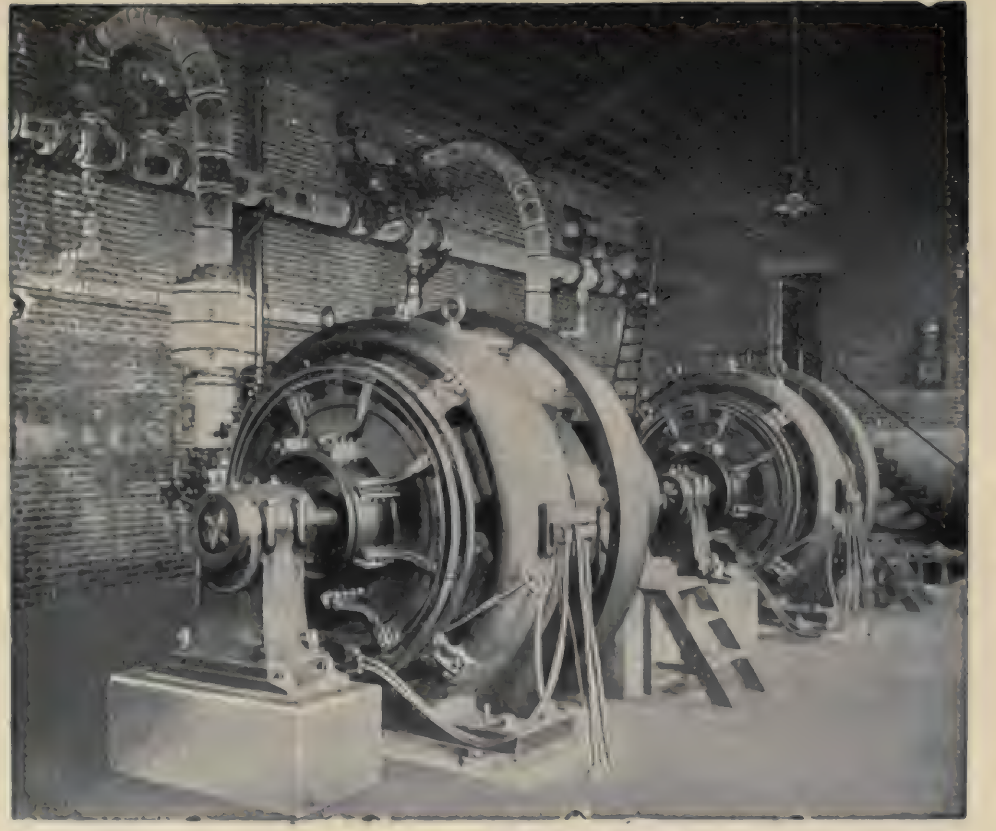
(*b*) End of First Quarter of Period of Commutation in Section *AB*.

(*c*) End of Second Quarter of Period of Commutation in Section *AB*.

(*d*) End of Third Quarter of Period of Commutation in Section *AB*.

(*e*) Commutation in Section *AB* Completed.

Fig. 67. Process of Commutation.—Brush Covering Two Segments



DIRECT-CONNECTED GENERATORS
Operating the Largest Woodworking Plant in the United States.
Triumph Electric Company.

Summary of Results. The considerations above indicated as to means for controlling the sparking at the commutators of continuous-current machines, may be summed up as follows:

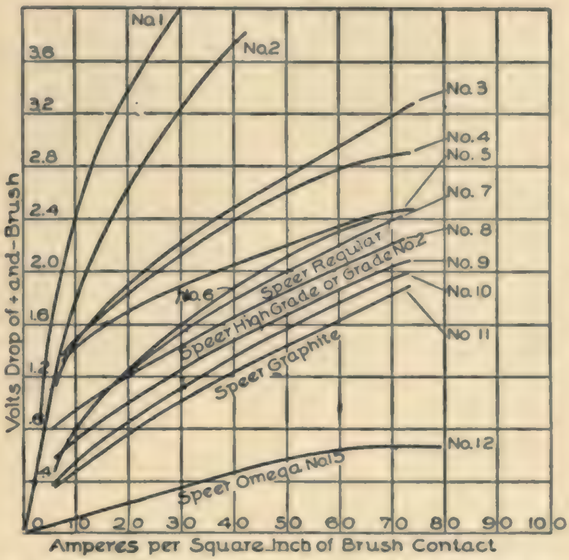


Fig. 68. Voltage-Drop Curves of Various Grades of Carbon and Graphite Brushes at Different Current-Densities.

(1) Keep the inductance of the armature coils low, by decreasing the number of turns per commutator segment, by saturating the teeth, and by properly shaping the pole-pieces to produce a reversal fringe.

(2) Keep the volts per segment of the commutator low by having a large number of commutator segments.

(3) Control distortion of the main flux in order to have the field under the hindward pole-horn sufficiently strong.

(4) Properly dimension and design the commutator-brushes,* brush-holders, and other brush-gear, so as to permit the shifting of the brushes to the proper position, and to enable the brushes to make contact with the commutator at all times.

(5) Keep the surface of the commutator smooth.

(6) Add special features to the machine.

To see clearly the application of most of these special features, it is desirable that we first consider another property of an armature carrying current—namely, its demagnetizing effect.

Demagnetizing Effect of Armature. To eliminate sparking at the commutator, we have seen that it is necessary to shift the brushes ahead of the neutral line in generators, and back in case of motors. The resultant effect is to produce in the armature a magnetomotive force (m. m. f.) opposed to that of the field-winding. Considering Fig. 69, wherein the brushes are supposed to be shifted to the line *nn'*, the remainder of the figure being as before, it is seen that the currents are flowing toward the observer in the armature conductors to the left of the neutral line nn', and from the observer in those to the right of that line. Now, suppose the two vertical lines *ad* and *bc* to be drawn across the section of the armature and through the points of commutation. The armature conductors are thus divided into two bands, those to the right of the line *ad* and to the left of the line *bc* tending to cross-magnetize the armature, while those included between these lines produce a m. m. f. opposed to that of the main field, since the current in these turns passes around the flux in a direction opposed to that of the field-exciting current. The breadth of the belt of demagnetizing windings is evidently proportional to the angle of lead, since it subtends double that angle. In such an armature generating 50 amperes, each conductor would carry 25 amperes, since there are two paths in parallel; and as the number of cross-magnetizing turns is 12, and the number of demagnetizing turns is 4, the "cross-ampere-turns" would be 25 × 12 = 300; and the number of "back ampere-turns" would be 25 × 4 = 100.

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* With respect to material and thickness, see Fig. 68.

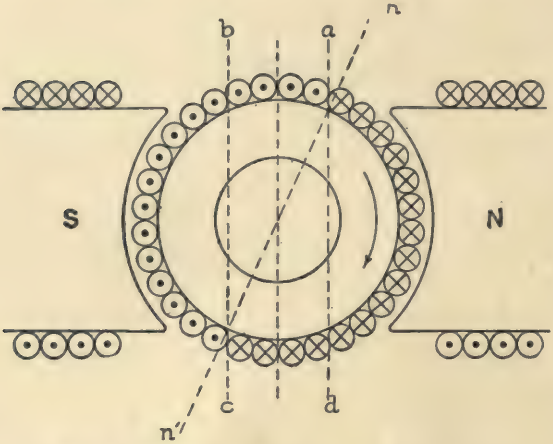

Fig. 69. Demagnetizing Action of Armature Current of Generator.

This demagnetizing influence, which is proportional to the angle of lead of the brushes, tends to weaken the field in general, while the cross-magnetization, proportional to the ampere-turns not included in the demagnetizing effect, tends to weaken the flux under the hindward pole-horn, and strengthen that under the forward pole-tip. Hence the impressed m. m. f. (that of the field-magnets) must be strong enough to force through the air-gap in the magnetic circuit sufficient flux to permit of sparkless commutation in spite of the demagnetizing effects. Since the cross-magnetization is responsible for the distortion which produces sparking, it remains to consider the remedies.

Cross-Reluctance Remedies. Fig. 70 shows that increased air-gap in the magnetic circuit *HAGDH* will diminish the cross-flux. This method is somewhat objectionable, however, because, in order to produce the same flux through the field-circuit, a greater m. m. f., and hence a larger number of field-exciting turns, are required. This disadvantage may be overcome in some types of generators by forming a V-groove in the polar mass behind the face, as shown in Fig. 71.

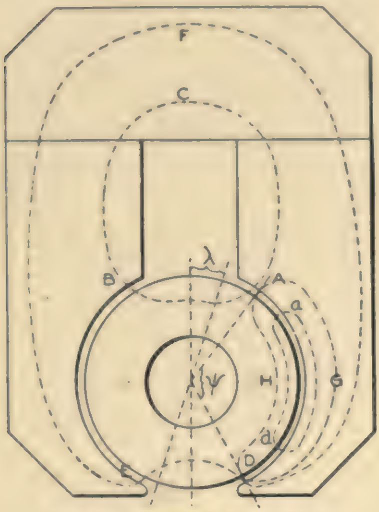

Fig. 70. Armature Interference.

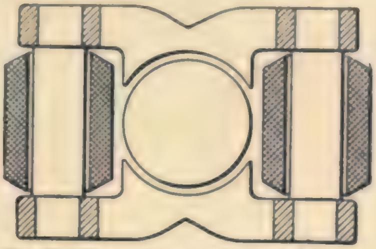

Fig. 71. Prevention of Cross-Reluctance by V-Groove in Back of Polar Mass.

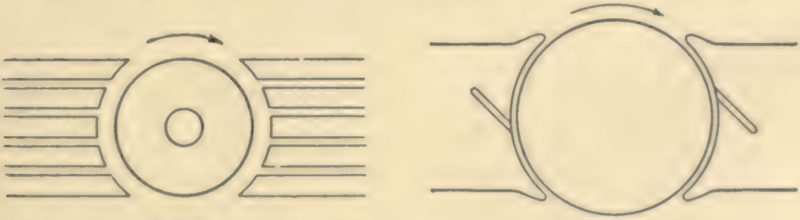

Fig. 72. Fig. 73.

Remedies for Cross-Reluctance.—Pole-Pieces Made with Longitudinal Gaps or Oblique Slots.

Another plan is to thin down or actually separate the two halves of the circuit, and thus throttle the cross-flux. S. P. Thompson has suggested constructing the field-cores of pieces of iron with longitudinal gaps, as indicated in Fig. 72, or slotting the pole-piece obliquely as in Fig. 73, the neck of the casting here becoming highly saturated and offering large reluctance to the cross-field.

Another arrangement consists in making the forward horn of cast iron, and the rearward horn of cast steel, the joint being oblique, as indicated in Fig. 74.

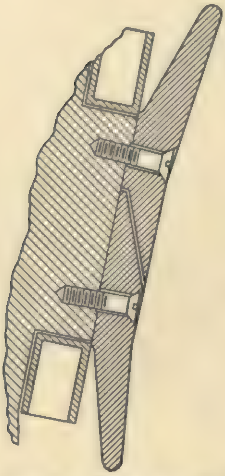

Fig. 74. Composite Pole-Shoe, Forward Horn Cast Iron; Hindward, Cast Steel, Meeting Obliquely to Minimize Magnetic Distortion at Full Load.

Cross-Compounding Remedies. Some designers provide a m. m. f. equal but opposed to the cross-magnetic m. m. f. Elihu Thomson placed a series ("compounding") coil on a separate frame surrounding the armature, and tilted it in a direction counter to the rotation so as partially to counteract the cross-flux. Swinburne suggested that a small auxiliary coil in series with the armature be wound around the pole-tip in order to maintain a field for reversal at this point (Fig. 75,*a*).

Menges, Mather, Swinburne, and others have advocated the use of auxiliary poles at right angles to the main poles, excited by coils in series with the armature. This feature is now embodied in the *Inter-pole* motor. S. P. Thompson proposed the use of compound winding having series and shunt coils at different angles, so that, as the armature reaction tended to shift the main flux forward, the increased current in the series coils would produce a m. m. f. tending to drive it back. Menges suggested winding series turns upon the polar parts of machines with double magnetic circuits. He was the first to suggest (1884) a cross-compound winding having the auxiliary poles set to produce a flux at right angles to the main flux.

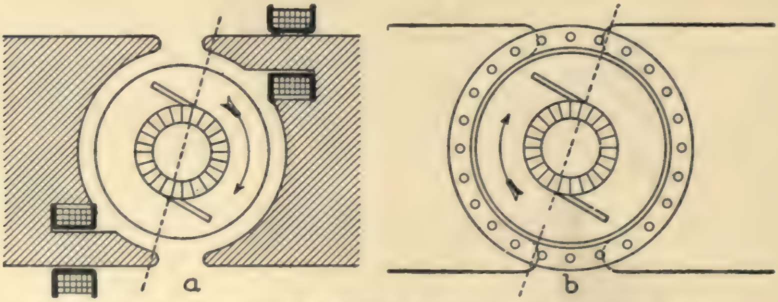

Fig. 75. Devices for Sparkless Collection of Current—(*a*) Swinburne; (*b*) Hutin and Leblanc.

Fisher-Hinnen, Professor Forbes, Mordey, and S. P. Thompson wind these coils in a notch at the center of the pole-face. Elihu Thomson also suggested the use of *unwound* auxiliary poles at right angles to the main poles, thereby leading off the cross-flux to strengthen the main flux.

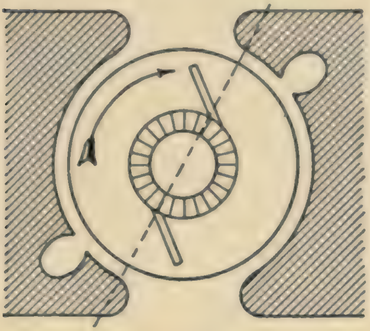

Fig. 76. Sayers' Device for Sparkless Collection of Current.

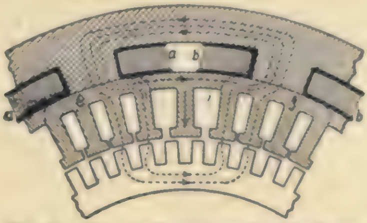

Fig. 77. Ryan's Compensating Devices.

The most complete solution was proposed independently by Professor Ryan and Fisher-Hinnen, who insert a number of coils in slots cut in the face of the pole parallel to the shaft, the coils being connected in series with the external circuit, and constituting a stationary winding which produces a m. m. f. equal but opposed to that due to the armature, Fig. 77. This device is not extensively

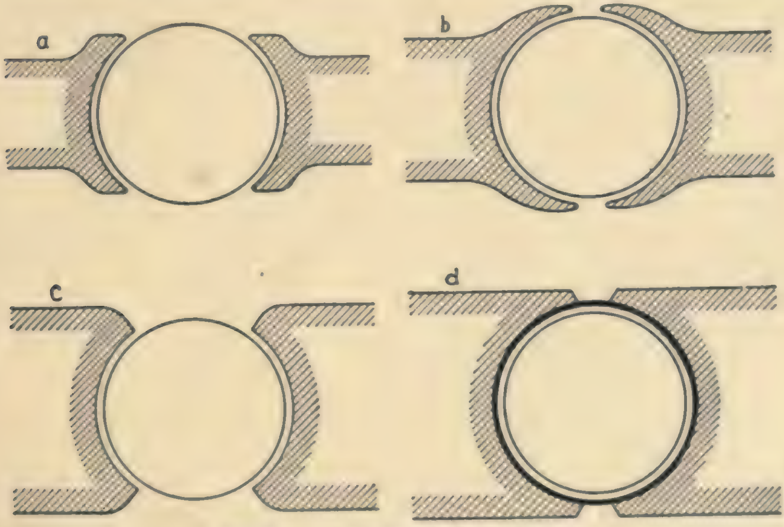

Fig. 78. Various Forms of Pole-Tips.

employed, however, on account of the increased heating as well as complication and cost.

Hutin and Leblanc proposed the placing of rods of copper in the pole-face, which rods are short-circuited upon themselves. This arrangement is intended to prevent oscillations in the direction of the magnetic flux at commutation. It is much used in alternating-current machines, to facilitate parallel operation (see Fig. 75, *b*).

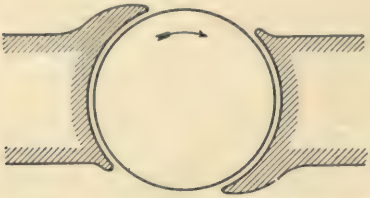

Fig. 79. Unsymmetrical Pole-Pieces Designed to Concentrate Field.

Concentration of Field. Sparkless commutation may also be accomplished if the field is magnetically rigid—that is, not easily distorted. This stiffness may be partially secured by properly shaping the pole-faces or by making notches in them (Fig. 76), as suggested by Sayers, thus concentrating the flux at the tip. In Fig. 78 are shown various forms of pole-tips, of which type *a* is not always good, but may be either extended as in *b*, or cut off as in *c*. An extreme arrangement, suggested by Dobrowolsky, surrounds the armature completely with iron, as in *d*.

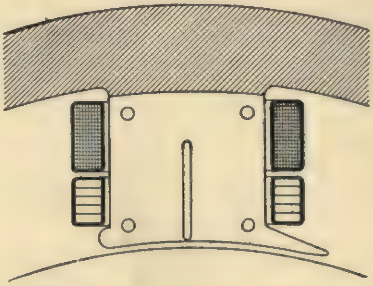

Fig. 80. Lundell's Form of Pole.

Another scheme, proposed by M. Gravier, employed the unsymmetrical form of poles shown in Fig. 79. When the machine is working at small loads, the flux in the gap is nearly uniform; but at large loads, the distortion due to armature current forces the flux forward and saturates the forward pole-horn, thus preventing much change in its flux-density, on account of the saturation and the diminished area. Lundell combines this device with the slotted-pole method, and produces the pole shown in Fig. 80. Another plan is to make the pole-cores of laminated wrought iron or steel, to which a cast-iron pole-piece is attached.

A similar effect is produced by making the poles non-concentric with the armature, as in Fig. 81. This secures a suitable fringe and at the same time maintains a fair magnetic rigidity. Mr. C. E. L. Brown finds that inwardly projecting poles of circular cross-section, without any pole-shoes or extensions, produce excellent results in generators which deliver large current. Other devices for securing a gradual entrance of the armature conductors into the field, are to skew the hindward edge of the pole-shoe as indicated in Fig. 82; to shape the pole-shoes with polygonal ends, Fig. 83; or to provide clawed edges, Fig. 84. Some manufacturers leave out every other lamina in the pole-tips, the resulting extra saturation helping to resist the effects of armature distortion. A somewhat similar device is that patented by Marshall, which consists in attaching to the pole-piece groups of short, laminated iron plates with narrow spaces between them, thus reducing the net area of the shoe, while preserving the same effective area.

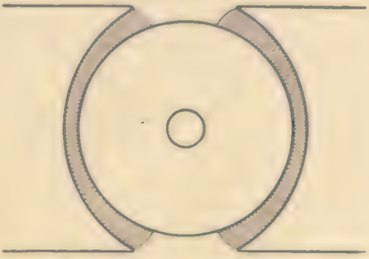
Fig. 81. Non-Concentric Poles.

Self-Compensating Armatures. The devices of Swinburne and Mordey, which relate to chord winding, have met with considerable success. The most prominent of these methods is that of Sayers, who connects the commutator-bars to the armature winding through auxiliary compensating coils. One end of each commutator coil, Fig. 85, is attached to the junction between two main armature coils, and the other end is connected to a commutator segment. The armature and commutator coils are represented while short-circuited by the brush, a rapid reversal of current being produced by the commutator coil and auxiliary pole. With this method of winding, the

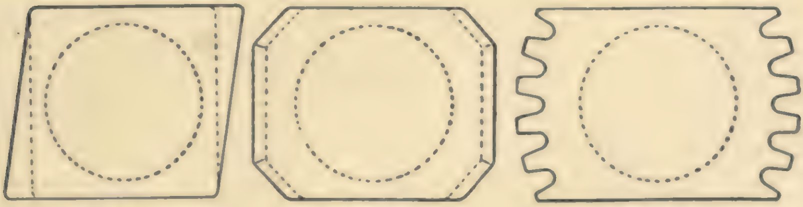
Fig. 82. Fig. 83. Fig. 84.

Devices for Securing Gradual Entrance of Armature Conductors into Field.

brushes may be given a backward lead, thus making the generator self-compounding without a series field-coil.

This completes the list of special features that may be added to generators or motors to eliminate sparking at the commutator; but most of these methods are not likely to be employed, on account of increased complications and reduced efficiency. In the largest machines built by the best manufacturers, none of these special features are present, because it is found that the heating limit of the machine is usually reached before sparking occurs. One prominent designer pays no attention to armature reaction, but relies upon a large number of commutator segments to keep the e. m. f. per segment at a very low figure, also minimizing the self-inductance of each armature coil by making it of few turns and of short length parallel to the shaft. For medium sizes or high-speed work, this design is now much used, especially where large distorting effects are present.

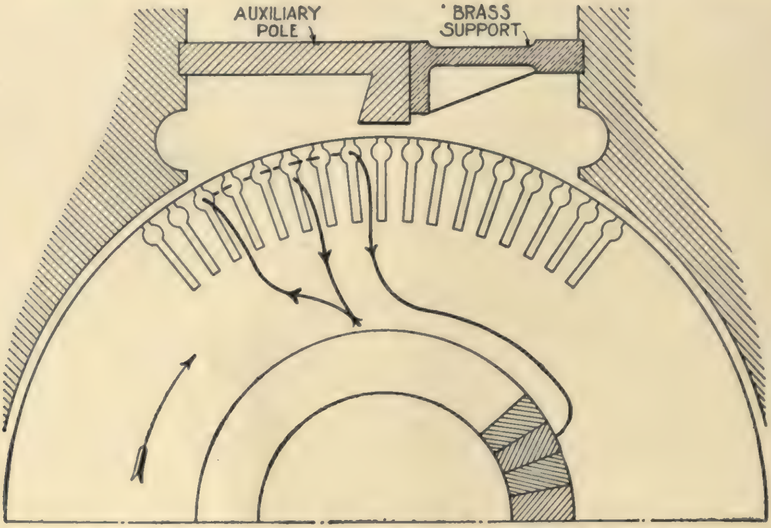

Fig. 85. Sayers Compensating Winding, with Commutation Coils.

Conclusions. The special points to be observed in order to prevent sparking at the commutator may therefore be stated as follows:

1. The armature ampere-turns per pole should not exceed certain definite values in machines of a given type. If the volts per commutator segment are 5 or less, the armature ampere-conductors should not exceed

20,000 per pole; while with 10 volts per segment, the ampere-conductors should not exceed 10,000.

2. Long air-gaps are unnecessary if the armature teeth are highly saturated—that is, have a flux-density of from 20,000 to 23,000 apparent lines* per square centimeter, or 125,000 to 150,000 apparent lines per square inch, both of the injurious effects of armature reaction being diminished.

3. Armatures should be as short as possible in order to reduce the self-inductance of the armature coils.

4. Number of volts per commutator segment should be low.

5. Inductance of the short-circuited coils should be low compared with brush-contact resistance, and the current-density in carbon brushes should be about 35 amperes per square inch.

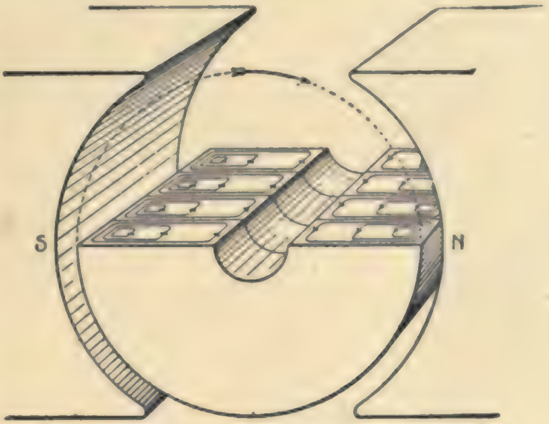

Fig. 86. Eddy Currents in Core-Discs.

Dead Turns. On account of the various internal reactions present in the armature, the terminal voltage is not quite proportional to the speed with constant field-current. Inasmuch as the machine acts as though some of its speed were ineffective, the name *dead turns* has been given to those revolutions by which the actual speed at any output exceeds that determined by strict proportionality.

Spurious Resistance. There is present in every rotating armature an apparent resistance proportional to the speed, due to the self-induction of the armature, as first pointed out by Cabanellas. It cannot be reduced by dividing the armature conductors into a greater number of segments, but can be made less by decreasing the number of conductors and increasing the cross-section of iron in the magnetic circuit. Its value is lessened by the introduction of a counter-e. m. f. aiding the commutation of the current, as previously explained.

Eddy Currents. In discussing the magnetic circuit, it was shown that parasitic currents may be produced in the iron parts of generators if any of these parts form closed electrical circuits and cut flux. In the armature, the iron core rotates in a magnetic field; eddy currents are set up in this core, as shown in Fig. 86, and unless prevented from flowing, these currents will lower the efficiency of the machine. Eddy currents will also be produced in the pole-faces, due to the variation of the magnetic flux, as shown in Figs. 87–92; and they may in addition manifest themselves in the armature conductors if the latter are large.

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* By *apparent lines per square centimeter in the teeth* is meant the flux-density which would be present in the teeth if all the flux issuing from the poles entered the armature core through the teeth.

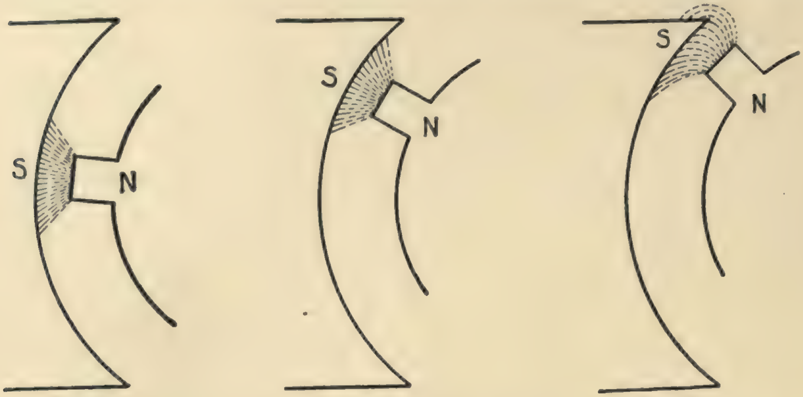


Fig. 87. Fig. 88. Fig. 89.

Alteration of Magnetic Field Due to Movement of Mass of Iron in Armature.

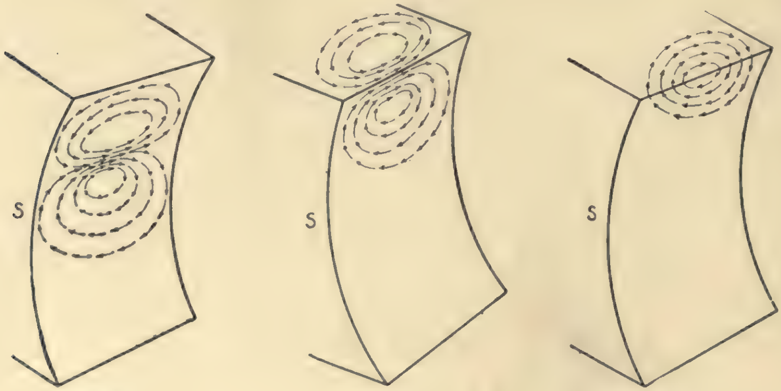


Fig. 90. Fig. 91. Fig. 92.

Eddy Currents Induced in Pole-Pieces by Movement of Masses of Iron.

In all cases where eddy currents are likely to be large, the circuits affected are laminated so that the plane of lamination cuts across the path of this parasitic current.

Drag on Armature Conductors. A conductor carrying a current is surrounded by a magnetic field, as shown on page 2. If, now, such a conductor be placed in a uniform magnetic field—as, for example, between a large north pole and a large south pole—a compound field will result, having the distorted appearance shown in Fig. 93. The direction of the mechanical force exerted may be determined by supposing that the flux acts as a bundle of elastic cords tending to shorten themselves. As a matter of fact, there is tension in the direction of the flux, and stress at right angles to it, proportional at every point to the square of the flux-density. A conductor in which current is supposed to be flowing toward the observer will therefore be urged in the direction of the arrow, Fig. 93; so that in every dynamo-electric machine the current generated produces a mechanical reaction which tends to stop the motion producing them.

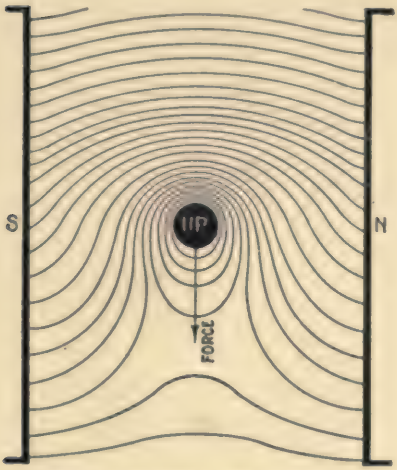


Fig. 93. Magnetic Lines Due to Conductor Carrying Current Placed in Magnetic Field.

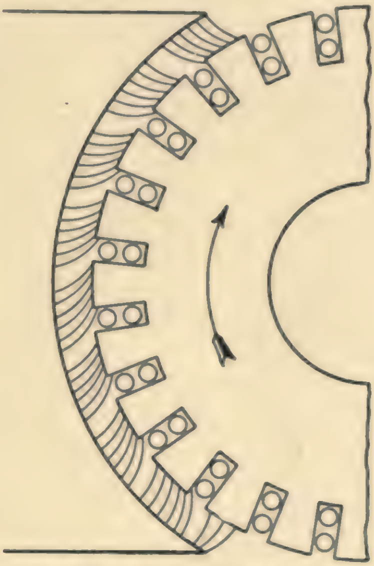


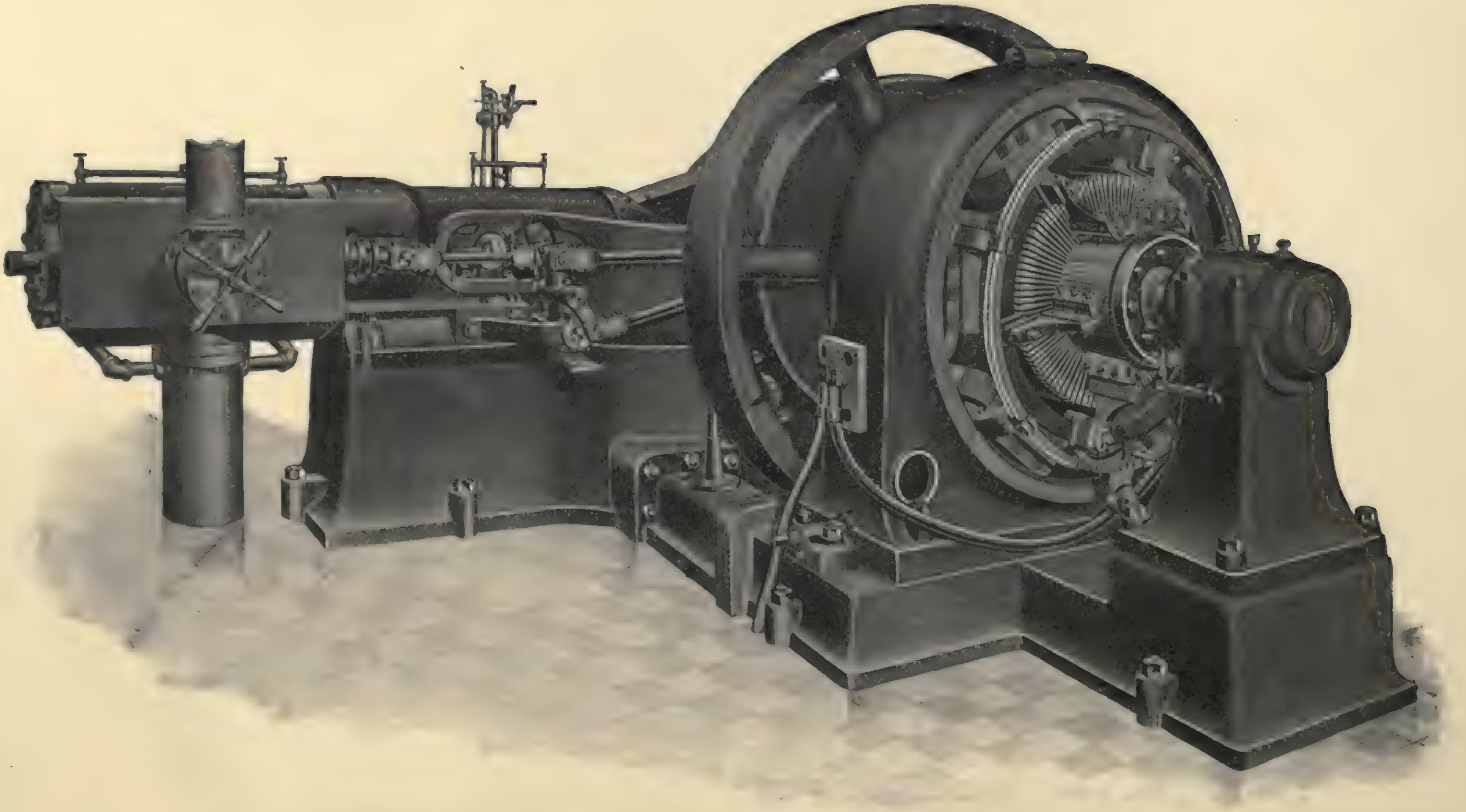
Fig. 94. Magnetic Field of Slotted Armature.

If the conductors are imbedded in slots or holes in the armature core, Fig. 94, it is found that the drag comes upon the iron, the magnetic field being distorted as shown. In fact, the flux no longer directly cuts the conductors, but, as it were, flashes from tooth to tooth. In addition to thus relieving the conductors of the drag effect, the teeth permit a much smaller air-gap to be used, sometimes reducing it to a mere mechanical clearance.

Stray-Power. In all practical machines there is a difference between the input and the output. In electrical machines, this discrepancy is caused by the following reactions:

1. Armature-resistance drop producing I^2R effects.
2. Friction of bearings and brushes.
3. Air-friction of the rotating armature.
4. Hysteresis in the armature core.
5. Eddy currents in the armature core, conductors, and polar projections.
6. Energy is also consumed in the field winding, due to I^2R effects.

Nos. 2, 3, 4, and 5 are grouped under the head of *stray power losses*, being from 40 to 60 per cent of the total loss. No. 3 is small, except in those cases where the armature spider is provided with fans to aid ventilation, and where special ventilating ducts are provided in the armature, as in most modern machines. No. 4 is by no means negligible, but never adds more than 1 per cent to the driving power. No. 5 is the most important of all, especially in large machines. It makes its presence felt even in the metal of the shaft, and there will be power wasted if flux leaks through this portion.



HEAVY DUTY, SIMPLE ENGINE DIRECT CONNECTED TO D. C. GENERATOR.
Buckeye Engine Company

DYNAMO-ELECTRIC MACHINERY

PART II

CALCULATIONS AND CHARACTERISTIC CURVES OF DIRECT-CURRENT DYNAMOS

Symbols. The symbols used in the discussions now to be taken up, are as follows:

b — Number of external wires in a section of the armature.
c — Number of circuits in parallel through an armature.
E — Entire e. m. f. generated in an armature, in volts.
e — Lost volts, or potential drop in volts, of armature.
η — Commercial efficiency.
η_1 — Economic coefficient, or electrical efficiency.
η_2 — Gross efficiency, or efficiency of conversion.
F — Force—*i.e.*, push or pull—in pounds' weight.
ϕ — Flux per pole.
I — Current in external circuit, in amperes.
I_a — Current in armature circuit, in amperes.
I_{sh} — Current in shunt field-exciting coil, in amperes.
I_{se} — Current in series field-exciting coil, in amperes.
K — Number of commutator segments.
L — Coefficient of self-induction, or inductance, in henrys
λ — Angle of lead of brushes.
M — Volts per revolution per second.
μ — Magnetic permeabilty.
n — Revolutions per second.
ν — Coefficient of magnetic dispersion, or leakage coefficient
p — Number of poles.
q — Ampere conductors per inch of periphery of curvature.
R — Resistance of external circuit, in ohms.
r — Total internal resistance of generator, in ohms.
r_a — Total resistance of armature *coils*, in ohms.
r_{sh} — Resistance of shunt field-exciting coils, in ohms.
r_{se} — Resistance of series field-exciting coils, in ohms.
r.p.m. — Revolutions per minute.
ψ — Angle of pole span.
σ — Space-factor.
T — Number of turns.

T_{sh} – Number of field-exciting turns in shunt with armature.
T_{se} – Number of field-exciting turns in series with armature.
t – Time in seconds.
V – Volts at terminal of a generator.
v – Velocity in feet per second.
W – Power in watts.
ω – Angular velocity in radians per second.
y – Winding pitch.
y_f – Forward winding pitch.
y_b – Backward winding pitch.
Z – Number of conductors on the armature, counting all around periphery.

Fundamental Equation. We have seen on page 17 that an e. m. f. of one volt is generated when 10^8 lines are cut per *second*. Now, as most armatures have more than one conductor cutting the field flux, the e. m. f. generated will be a direct function of the number of conductors connected in series.

Assuming that the sections of the armature winding equal in number the commutator bars (K), the external conductors all around the armature will be bK. The total number of conductors that are in series with each other electrically from brush to brush is $\frac{bK}{c}$ or $\frac{Z}{c}$. If, now, the armature speed of rotation is given in r. p. m., then the revolutions per second $(n) = \frac{\text{r. p. m.}}{60}$.

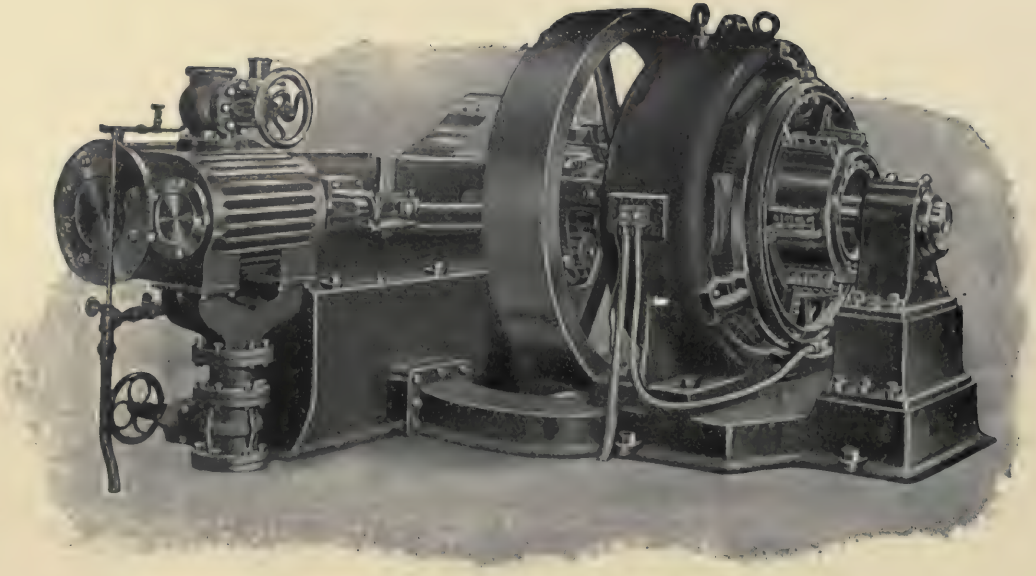
In order to compute the e. m. f. generated, we have:

Number of lines cut by one external wire in one revolution .... $= p\phi$
Number of lines cut by 1 external wire in 1 second .... $= np\phi$
Number of lines cut by $\frac{Z}{c}$ external wires in series in 1 second .... $= np\phi Z \div c$
Average e. m. f. generated, in C.G.S. units .... $= nZ\phi\frac{p}{}$
Average e. m. f. generated, in volts .... $= \frac{nZ\phi}{10^8}\,\frac{p}{c}$
Average e. m. f. generated, in volts .... $= \frac{\text{r. p. m.} \times Z\phi p}{60 \times 10^8 \times c}$ (1)

If the number of circuits through the armature is equal to the number of poles in the field, we may write:

$$(\text{Average})\ E = \frac{\text{r. p. m.} \times Z\phi}{10^8 \times 60} = Mn \quad \ldots\ldots\ldots\ldots\ldots (2)$$

It must be remembered that this e. m. f. is an average, and that it



100 K.W. ENGINE-TYPE GENERATOR AND AUTOMATIC HIGH-SPEED ENGINE.

Triumph Electric Company.

depends upon the construction of the armature how much fluctuation takes place during a rotation, as shown on page 22.

Example. Assume a 4-pole machine with a 4-circuit armature winding; the flux per pole, 2,000,000 lines of force; the total number of inductors in the armature, 600; and the speed of the machine, 1,200 r. p. m. Determine the generated voltage.

Substituting in Equation 1, we have;

$$E = \frac{1{,}200 \times 600 \times 2{,}000{,}000 \times 4}{60 \times 10^8 \times 4} = 240 \text{ volts.}$$

Efficiency of a Generator. The efficiency of a generator is defined to be the ratio of the mechanical power applied to the rotation of the armature of the generator at any given load, to the electric power output at that load. The mechanical power expended in turning the armature against the resisting forces may be measured mechanically by a dynamometer, or by taking indicator cards at the engine and allowing for friction. By far the best method is the electrical one, of using an electric motor, which has been carefully calibrated, to determine the mechanical power required to operate the generator at any given load. The Hopkinson or so-called *pumping-back* arrangements are even more commonly adopted, especially for large units.

The electrical power is expressed as the product of amperes of current and volts difference of potential between the two terminals of that part of the circuit in which the energy is being expended. This product, measured by suitable instruments, expresses the power or energy expended per second in the circuit in watts, the electrical unit of power. The mechanical unit of power (that is, the horse-power, h. p.), is practically equal to 746 watts*. We may therefore write,

$$\text{h.p.} = \frac{W}{746} = \frac{I \times V}{746} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

The electrical efficiency or economic coefficient of a generator is defined to be the ratio between the electrical power utilized in the external electrical circuit and the electrical power developed in the armature. So that if, through an armature there are flowing I_a amperes due to a generated e. m. f. (E), the electrical activity expressed in watts will be EI_a.

---

* 1 h. p. = 745.560 watts exactly (Henry's *Conversion Tables*).

If the voltage at the terminals of the generator be V volts, and the current through the external circuit be I amperes, the useful power in watts will be $V \times I$.

Therefore the *economic coefficient* of the machine will be:

$$\eta_1 = \frac{\text{Useful electrical power}}{\text{Total electrical power}} = \frac{V \times I}{E \times I_a}.$$

The efficiency of electric conversion is defined as the ratio of the power developed in the armature to the mechanical power expended in producing it. This may be written:

$$\eta_2 = \frac{EI_a}{746 \times \text{h. p.}}.$$

Hence the commercial or true efficiency of the generator becomes:

$$\eta = \eta_1 \times \eta_2 = \frac{VI}{746 \times \text{h. p.}}.$$

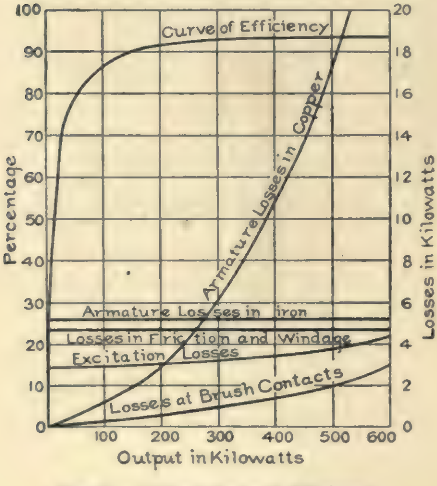


Fig. 95. Typical Curve of Efficiency.

It may also be obtained by taking the ratio between the output in watts, and the sum of the output and losses in watts; that is,

$$\eta = \frac{VI}{VI + \Sigma W'};$$

in which $\Sigma W'$ represents the sum of the mechanical and electrical losses in the generator. By multiplying the right-hand member of this last equation by 100, the commercial efficiency is obtained as a percentage.

The efficiency of a generator is by no means constant throughout all ranges of loading. On the contrary, because of the variation of the generator losses with the current through the armature, the efficiency curve takes some such form as that shown in Fig. 95. Here it is seen that the efficiency increases very rapidly from 0 to about 80 per cent at 80 kilowatts output, beyond which it increases slowly until it reaches a maximum value at about 550 kw. From this point it decreases slowly; and with still further increase in load, the efficiency would continue to decrease, but more and more rapidly. This is made clear when the curves representing the variation of the losses with load are examined. Assuming speed and voltage constant, it is seen that the friction, windage, and iron losses increase very slowly with output. The copper losses in the armature and field, and the brush-contact losses, increase, however, as the square of the current, and thus at large overloads attain enormous proportions. By proper design, the efficiency curve may be made to take any desired form within certain limits, the maximum point being usually designed to occur at the normal load.

Magneto Generator. In this type of dynamo the flux through the armature is due to the permanent field magnets. Thus ϕ depends both upon their magnetic strength and upon the cross-section of iron core of the armature and the air-gaps. If the current drawn from the machine is sufficiently great, the reaction of the armature will diminish ϕ, and lessen the generated e. m. f. (assuming constant speed of rotation). If, however, the current drawn produces a negligible effect upon the flux through the armature, the voltage of any given magneto machine will be directly proportional to the speed of rotation, by Equation 1, page 62.

The voltage at the terminals of the magneto as well as other types of electric generators, is not equal to that generated in the armature conductors. The armature winding is always of appreciable resistance, so that the passage of any current through it produces a drop of potential, in addition to which there is also a drop due to the brush-contact resistance. It is convenient to have an expression for E in terms of the terminal voltage V and other measurable quantities, because E cannot be measured directly when any current is being drawn.

Let r be the total internal resistance of the armature of the generator, measured at the brushes; let R be the total external resistance; and let I be the current. Then by Ohm's law,

$$E = I(R + r) \qquad (4)$$

$$e = Ir$$

$$V = IR;$$

so that,

$$\frac{V}{E} = \frac{R}{R + r} \qquad (5)$$

and

$$E = V + Ir = V + e \qquad (6)$$

which means that the generated e. m. f. is equal to the sum of the terminal voltage and the armature-resistance drop. This latter increases directly with the armature current, but in well-designed machines is arranged so as not to exceed 2 or 3 per cent at rated load.

On page 64 the economic coefficient was shown to be

$$\eta_1 = \frac{V\,I}{E\,I_a}.$$

In the magneto machine, $I = I_a$; so that, from Equation 5,

$$\eta_1 = \frac{V}{E} = \frac{R}{r + R} \quad \text{.......................(7)}$$

This equation shows that as the resistance of the armature is decreased, the economic coefficient of the machine increases, the *theoretical* maximum of unity being attained when the armature resistance is *nil.* This is true for all electrical machines.

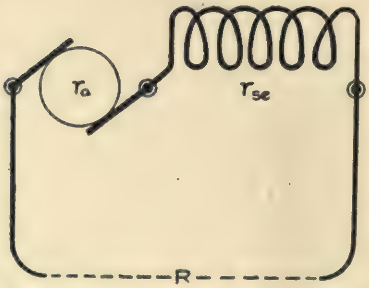


Fig. 96. Diagrammatic Representation of Series Generator.

Separately-Excited Generator. For this type of dynamo the same formulæ hold as for magneto generators. In this case, however, the flux per pole ϕ depends upon the strength of the field-exciting current secured from an independent source. In estimating the commercial efficiency, this fact must be taken into account, the power thus spent being usually from 1 to 3 per cent of the output of the machine, the larger figure relating to the smaller machines.

Series Generator. The series generator, shown diagrammatically in Fig. 96, has but one circuit and one current (I), whose strength depends upon the generated e. m. f. (E) and the total resistance in the circuit. Using the notation previously adopted, we have by Ohm's law:

$E = I\,(R + r_a + r_{se})$; and $V = IR$. Hence

$$V = E - (r_a + r_{se})\,I.$$

The economic coefficient will be:

$$\eta_1 = \frac{\text{Useful power}}{\text{Total power}} = \frac{I^2\,R}{I^2\,(R + r_a + r_{se})} = \frac{R}{(R + r^a + r_{se})} = \frac{V}{E} \quad \text{.....(8)}$$

This is obviously highest when r_a and r_{se} are *both* very small. They are usually about equal.

Shunt Generator. In the shunt dynamo, Fig. 97, the field and the external circuits are in parallel, so that we have two circuits to consider.

Let I = the current in the external circuit;
I_a = the current in the armature;
I_{sh} = the current in the shunt field-circuit.

Then,

$$I_a = I + I_{sh};$$

for it is clear that the current produced in the armature divides between these two parts of the circuit only.

Calling that part of the armature current which passes through the shunt winding and is consequently not available in the external circuit, the *lost amperes** = I_{sh}, we have the resistance of the shunt coils,

$$r_{sh} = \frac{V}{I_{sh}}.$$

In modern machines, r_{sh} is so proportioned that the shunt field amperes constitute from 1 to 3 per cent of the whole current output of the machine, the larger value being for the smaller generators.

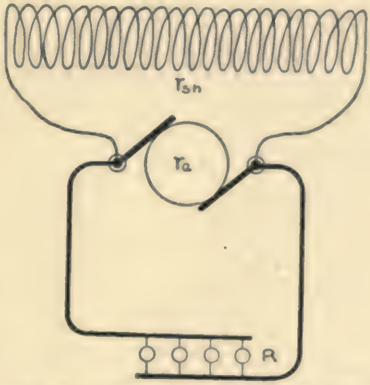


Fig. 97. Shunt Dynamo Showing Main and Shunt Circuits.

Example: In a standard Crocker-Wheeler 85 kw. shunt generator, 3.3 amperes was required in the field-exciting circuit, the generator giving 370 external amperes at 230 volts. Thus the resistance of the field winding was 69.7 ohms, the armature current was 373 amperes, and the shunt field current was about 1 per cent of the rated load current.

We may now compute the economic coefficient of a shunt-wound generator as follows:

The total watts produced in the armature of the machine are:

$$W = EI_a \ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

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*S. P. Thompson's *Dynamo-Electric Machinery*, N. Y., 1904, Vol. I, Page 300.

and the watts delivered to the external circuit are

$$w = V\,I \quad \ldots\ldots (10)$$

We also have

$$E = V + I_a\,r_a = V + (I + I_{sh})\,r_a\,, \quad \ldots\ldots (11)$$

since

$$I_a = I + I_{sh}$$

Substituting these values in Equation 9, we obtain:

$$\begin{aligned} W &= (V + Ir_a + I_{sh}\,r_a)\,(I + I_{sh}) \\ &= VI + VI_{sh} + (I + I_{sh})^2\,r_a \\ &= VI + VI_{sh} + I_a^2\,r_a \quad \ldots\ldots (12) \end{aligned}$$

which reads: The watts produced in the armature are equal to the sum of the watts delivered to the external circuit, the watts wasted in the shunt field, and the watts dissipated in heating the armature conductors. Considering, then, the purely electrical efficiency of a shunt-wound generator, the iron losses, friction, windage, and other mechanically supplied losses not being present in Equation 12, we have,

$$\eta_1 = \frac{w}{W} = \frac{VI}{VI + VI_{sh} + I_a^2\,r_a} \quad \ldots\ldots (13)$$

In order that this ratio may approach unity, its limit, the sum of the losses must approach zero. Writing the latter as a fraction of the output, we have,

$$\begin{aligned} \frac{1 - \eta_1}{\eta_1} &= \frac{V\,I_{sh} + I_a^2\,r}{VI} \\ &= \frac{I_{sh}}{I} + \frac{I_a\,r_a}{V} \quad \ldots\ldots (14) \end{aligned}$$

which shows that the two terms are of equal importance, assuming that $I_a = I$, *i.e.*, that the shunt-exciting current is negligible, as in practice it rarely exceeds 2 to 3 per cent of the rated current.

Equating these two terms, and inserting for I_{sh} its value $V \div r_{sh}$, there is obtained,

$$\frac{I\,r_a}{V} = \frac{V}{I\,r_{sh}} \quad \ldots\ldots (15)$$

that is

$$\frac{V}{I} = \sqrt{r_a\,r_{sh}} = R \quad \ldots\ldots (16)$$

showing that the external resistance is a geometric mean between the armature resistance and the resistance of the shunt-field winding.

Substituting in Equation 14, for I and V, their values in terms of resistances as given above, we have,

$$\frac{1-\eta_1}{\eta_1} = \frac{R}{r_{sh}} + \frac{r_a}{R} \quad \text{......................} \quad \textbf{(17)}$$

from which it is obvious, that for the percentage of losses to be small, the shunt-winding resistance must be large in comparison with the armature resistance.

It must be clearly borne in mind throughout the preceding discussions, that the *commercial efficiency* is always lower than the so-called "electrical efficiency," since the latter does not include the mechanically supplied losses due to friction, windage, hysteresis, and eddy currents. The economic coefficient, or electrical efficiency, may be used to compare various types and to show the conditions for best electrical working; but the commercial efficiency is the true and final test for any given machine.

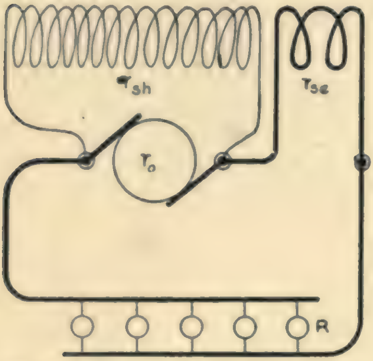

Fig. 98. Short-Shunt Method of Connecting Shunt-Coils to Dynamo.

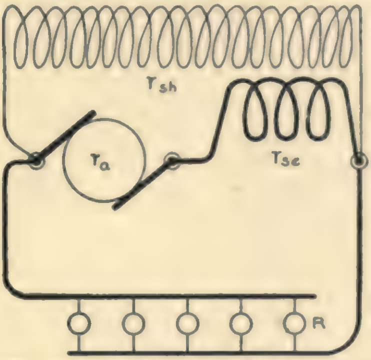

Fig. 99. Long-Shunt Method of Connecting Shunt-Coils to Dynamo.

Compound-Wound Generator. Under this head will be considered that type of compound dynamo in almost universal use at the present time. This may be regarded as either a shunt machine in which series turns have been added to the field winding in order to compensate for the drops due to armature resistance and armature reactions; or as a series generator to which shunt windings have been added in order to produce an initial magnetization. In either case, there are two possible ways of connecting the terminals of the shunt coils to the source of voltage, known respectively as the *short-shunt* and *long-shunt* methods.

In the short-shunt method, the shunt coils are connected directly across the brushes of the machine, Fig. 98; while in the long-shunt arrangement, Fig. 99, the shunt coils may be considered as a shunt to the external circuit. In the former method the voltage applied to the terminals of the shunt windings is not a constant, but increases with load if the generator be assumed to be compounded to give a constant or increasing terminal voltage with load. In the long-shunt method, the voltage at the terminals of the shunt coils will be the same as that impressed upon the external circuit; and if the generator is compounded to give constant terminal voltage, the arrangement becomes analogous to the case of a machine with one field-exciting winding supplied from an independent source at constant potential, and a second field-exciting winding in series with the external circuit.

The calculations for both long- and short-shunt arrangements are practically the same; but, on account of greater simplicity, those for the former, with the generator assumed to be compounded for constant terminal voltage, will be given.

We have from page 62, $E = M n$; also, $V = E - (r_a + r_{se}) I_a$. Since the flux depends upon the ampere turns of excitation

$$M = M_o + M_x = u\,(I_{sh}\,T_{sh} + I_{se}\,T_{se}), \qquad \text{(18)}$$

in which u is a variable quantity representing, at various stages of the magnetization, the numerical relation between the flux and excitation of the magnetic circuit for a particular dynamo. Consequently, when the external current is zero, we have:

$$M_o = u_o\,I_{sh}\,T_{sh}.$$

M is proportional to the flux entering the armature from one pole, which in compounded machines is not a constant quantity. It is due to the combined effects of the shunt and series ampere-turns; that is, $M = M_1 + M_x$, in which M_1 is proportional to the shunt ampere-turns, and M_x is proportional to the series ampere-turns.

From pages 10, 61, and 62, it is clear that,

$$M_x = \frac{0.4\pi\,I_{se}\,T_{se}}{\Sigma \dfrac{l}{\mu A}} \cdot \frac{Z\,p}{10^8 . c},$$

and

$$M_1 = \frac{0.4\pi\,I_{sh}\,T_{sh}}{\Sigma \dfrac{l}{\mu A}} \cdot \frac{Z\,p}{10^8 . c},$$

where μ is the *average* value of the gross permeability (iron and air together), between its two extreme values—that is, when I = zero, and I = maximum.

Adding the two preceding equations, we have:

$$M = M_o + M_x = \frac{Z\,p\,0.4\,\pi}{10^8 c\,\Sigma\dfrac{l}{\mu\,A}}(I_{se}\,T_{se} + I_{sh}\,T_{sh}).$$

Replacing the factor $\dfrac{Z\,p\,0.4\,\pi}{10^8\,c\,\Sigma\dfrac{l}{\mu\,A}}$ by u, the result is:

$$M = u\,(I_{sh}\,T_{sh} + I_{se}\,T_{se}),\text{ as above.}$$

Substituting the values of E and M, there is obtained:

$$V = n\,u\,I_{sh}\,T_{sh} + n\,u\,I_a\,T_{se} - (r_a + r_{se})\,I_a.$$

Inspecting this equation, we note that it is composed of three terms. The first contains as variable factors the speed of rotation and the shunt current, which latter may be kept constant if the terminal voltage can be made constant. The second and third terms contain as a variable factor, the current I_a, while the second contains also the speed as a variable. It is noted, however, that the algebraic signs of the second and third terms are opposite, and that, if the speed of rotation is constant, the latter terms contain the only variables. Therefore, in order that V may remain constant throughout all changes of load within the rating of the machine, these terms must cancel. That is, $n\,u\,T_{se} = r_a + r_{se}$ is an equation of condition for constant V at constant n. Dividing both sides by $n\,u$, or by $u\,T_{se}$, there results:

$$T_{se} = \frac{r_a + r_{se}}{n}\cdot\frac{1}{u}\text{ ; or, } n = \frac{r_a + r_{se}}{T_{se}}\cdot\frac{1}{u}.\ \ldots\ldots\ldots\ldots\ldots (19)$$

When the external current is zero,

$$V = n\,M_o - (r_a + r_{se})\,I_a\,;$$

and assuming the drops due to the resistances of the armature and series field-windings to be zero (since they are negligibly small when the external current is zero), we have:

$$V = n\,u_o\,I_{sh}\,T_{sh} = I_{sh}\,r_{sh}.$$

Substituting value of n from Equation 19, we have:

$$\frac{r_{sh}}{T_{sh}}\cdot\frac{1}{u_o} = \frac{r_a + r_{se}}{T_{se}}\cdot\frac{1}{u}\text{ ; or, }\frac{T_{sh}}{T_{se}} = \frac{r_{sh}}{r_a + r_{se}}\cdot\frac{u}{u_o}\ \ldots\ldots\ldots (20)$$

which is the final equation of condition that V shall be constant.

As u_0 is proportional to μ_0, the permeability of the magnetic circuit when the external current is zero, and as u is proportional to μ, the average permeability over the working range, it follows that if there were no alteration due to saturation, we should have $u = u_0$.

Thus far we have assumed that the difference between the generated e. m. f. and the terminal voltage of the machine was dependent upon the resistances of the armature and series-field windings; but, as we have seen on page 49, there is also a drop due to the armature demagnetizing action. In order to take account of this, we must remember that if the angle of lead of the brushes be λ, the demagnetizing conductors will be confined within a belt 2λ (*i.e.*, $Z\lambda \div 90°$). Then, if the number of paths through the armature be c, each conductor will carry $I_a \div c = I_1$ amperes; and the number of demagnetizing ampere-turns will be $2DI_1$, where D is the number of armature conductors within the angle λ. In order to compensate for this action, a number of turns must be added to the series regulating turns, such that the m. m. f. produced by the external current flowing through them shall be exactly equal but opposed to that produced by the demagnetizing tendency of the armature. That is, the compensating turns must be at least,

$$\frac{2\,I_1\,D}{I} = \frac{2\,D}{c}\,.$$

Owing, however, to the effect of magnetic leakage, the total m. m. f. of this compensating winding will not be sufficient to void the armature demagnetizing effect. This leakage may be provided for by multiplying $2\,D \div c$ by ν, the coefficient of magnetic leakage. Hence we must substitute for T_{se} in Equation 20, $T_{se} - \frac{2\nu D}{u}$, in order to compensate for these effects.

Should it be required to have the generator over-compound or under-compound, the additional series-turns will be either more or less than those given by the revised Equation 20, depending upon the amount of over- or under-compounding, examples of which will be considered under *Design*. In the above discussion, we tacitly assumed that the speed of rotation was maintained constant. This is in general not the case, however, the speed of the prime mover falling off as the load on the generator increases, producing a diminution in the generated e. m. f. In addition, the load is frequently remote from the dynamo, necessitating feeders between the machine and load, with a consequent drop in voltage. In order to compensate for these factors which tend to lower the voltage at the point of application of the power, it is customary to over-compound generators so that their terminal voltage at rated load is from 3 to 15 per cent in excess of the no-load value. The lower values are usual for generators supplying lighting circuits, while the higher ones are for those employed in railway systems.

CALCULATIONS OF THE MAGNETIC CIRCUIT

Forms of Field-Magnets.—*General.* Before discussing the application of the formulæ for the magnetic circuit, already given, to actual machines, let us consider the various shapes in which field-magnets and frames are usually found.

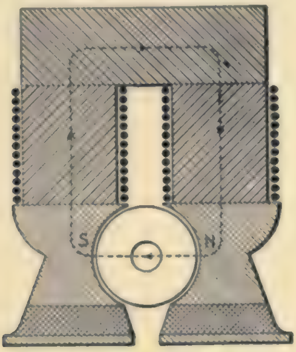

Fig. 100. Under-Type Bipolar Dynamo.

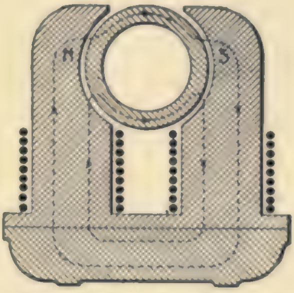

Fig. 101. Over-Type Bipolar Dynamo.

The form of a field-magnet depends primarily upon whether it is *bipolar* or *multipolar.* Prior to about 1890, the former type was in universal use for all direct-current machines, even up to large sizes; but now it is generally restricted to machines of less than 5 kilowatts output, larger sizes being made multipolar to save material, as explained later.

Bipolar field-magnets may be of the simple horseshoe type, placed as in the early Edison machines (Fig. 100); or may be turned with the pole-pieces upward, known as the *inverted* or *over-type* (Fig. 101); or the horseshoe may be laid on its side (Fig. 102). This latter type produces an unsymmetrical machine, and, in addition, the entire base and bearings are connected to one of the pole-pieces, exposing a large surface which materially increases the magnetic leakage. This type is interesting, however, from the fact that it has but a single field-coil. The same form is also arranged with the core horizontal, the armature being either under or over the latter, in which case the supports for the bearings must be of some non-magnetic material such as brass, since they extend from one pole-piece to the other.

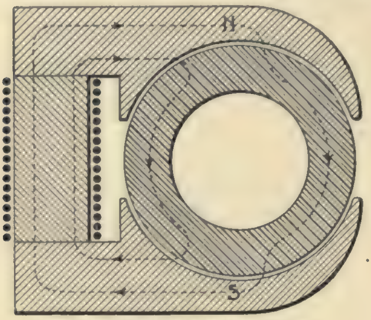

Fig. 102. Single Exciting-Coil Type Bipolar Dynamo.

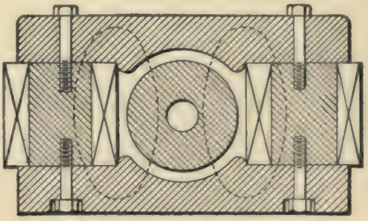

Fig. 103. Manchester Type of Field-Magnet.

These forms, excepting the over-type, are open to the objection that, if set upon an iron base, the base would act as a magnetic short-circuit, and thus rob the armature of a considerable portion of the magnetic flux. In the Edison machines, this difficulty was partly overcome by interposing thick pieces of zinc between the pole-pieces and the base; but Hopkinson* found that even with this arrangement,

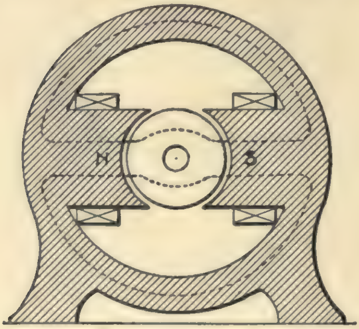

Fig. 104. Bipolar Ring Field-Magnet.

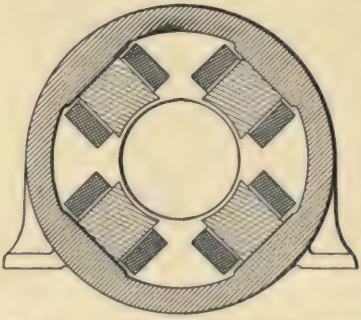

Fig. 105. Four-Pole Ring Field-Magnet.

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*Philosophical Transactions of the Royal Society, May 6, 1886.

the leakage through the base was over 10 per cent of the total flux. The over-type, on the other hand, has but small magnetic leakage of this character, since the pole-pieces are far removed from the base bearings or other magnetic conductors.

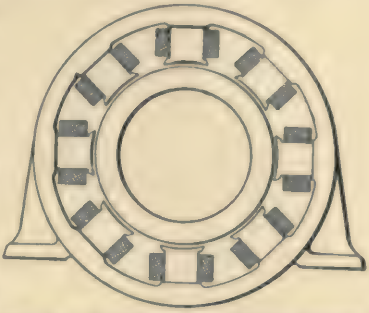
Fig. 106. Multipolar Ring Field-Magnet.

Fig. 103 represents a radically different form of bipolar magnet, called the *Manchester* type, from its place of manufacture in England. The construction is extremely solid, and offers good protection to the machine; but it has the undesirable feature of having two magnetic circuits in parallel, producing consequent poles and requiring the full number of ampere-turns for each circuit. Hence the total number is doubled; but each is only $\sqrt{\frac{1}{2}}$ times as long, because the cross-section of each core is one-half that of an equivalent single core. The required length of wire is thus $2 \times \sqrt{\frac{1}{2}} = 1.41$ times as great for the double magnetic circuit. This form also has considerable magnetic leakage, the entire base and bearings being connected to one of the pole-pieces.

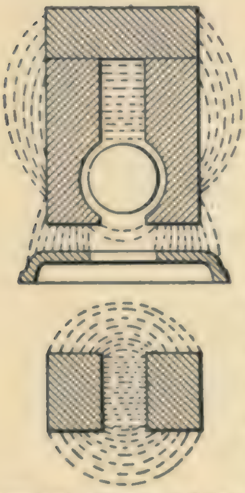
Fig. 107. Magnetic Leakage or Stray Flux in Bipolar Field.

The modern tendency has been to draw away from these early designs, and to adopt machines that are wholly or partially enclosed. Figs. 104, 105, 106 represent respectively the bipolar, four-pole and multipolar ring arrangements of present-day practice, the bipolar type being restricted to machines of small output, as noted above. This ring arrangement has the advantages of strength, simplicity, symmetrical appearance, and minimum magnetic leakage, since the pole-pieces have the least possible surface and the path of the magnetic flux is shorter, more symmetrical, and more natural.

Magnetic Leakage. The function of the field-magnet is, as we have seen, to produce a flux which the armature conductors cut in order to generate an e. m. f. This flux is called the *useful* flux. In addition to this useful flux, there is a *stray* flux from all parts of the field system (Figs. 107, 108), the m. m. f. of the exciting ampere-turns having to produce both these fluxes. If we call ϕ_m the flux in the magnet-core, ϕ_a the flux in the armature, and ϕ_s the flux which strays, we have:

$$\phi_m = \phi_a + \phi_s$$

The ratio between the total flux and the useful flux is called the *coefficient of magnetic leakage or dispersion,* that is,

$$\nu = \frac{\phi_m}{\phi_a}.$$

It is a number greater than unity, and varies in value from 1.15 in ring types (Figs. 104–106), to 1.7 in the Manchester and under-types (Figs. 100–103).

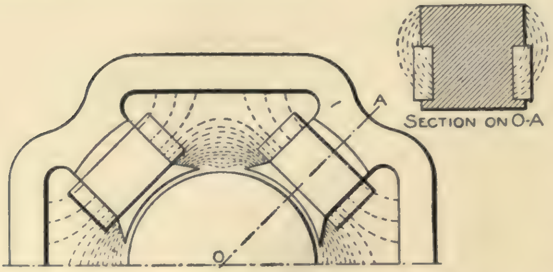

Fig. 108. Magnetic Leakage or Stray Flux in Four-Pole Field.

The magnitude of the stray field depends chiefly (*a*) upon the shape of the magnet-limbs; thus circular cores, for example, will have less leakage than those of rectangular cross-section, on account of the smaller area of the side flanks; (*b*) upon the length of the air-gap, because the higher the reluctance of the latter, the greater the tendency of the flux to take alternative paths; (*c*) upon the degree of saturation to which the field system is pushed, because the magnetic conductivity of the leakage paths in air is constant, while that of the iron cores decreases as the saturation point is approached. It is evident, therefore, that the coefficient of dispersion not only varies with different types of machine, but is not generally constant even in a given machine, since it rises with the excitation. Moreover, when a large armature current flows, the demagnetizing action of the latter directly aids dispersion, as it usually produces a m. m. f. opposed to that of the main flux, which tends to blow aside the latter.

The only accurate method of determining the dispersion factor of any machine is by experiment.* For purposes of design, however,

---

*For various methods of procedure, see S. P. Thompson's *Dynamo-Electric Machinery,* Vol. I, p. 134, New York, 1904.

one must resort to the results of experiments performed on machines similar to the one being designed. Table II gives approximate values of dispersion coefficients for machines of the modern type (*i.e.*, multipolar frames), and — for comparison — values for corresponding machines of the other types mentioned.*

TABLE II

Dispersion Coefficients

Output in Kilowatts	Multipolar Type Figs 104, 105, 106	Overtype Fig. 101	Undertype Fig. 100	Single-Magnet Type Fig. 102	Manchester Type Fig. 103
1	1.35				
2	1.25				
5	1.20	1.40	1.60	1.55	1.70
7	1.18				
10	1.16				
25	1.15	1.28	1.45	1.40	1.55
50	1.14				
100	1.12	1.22	1.35	1.32	1.45
200	1.11				
300	1.10		1.25		
500	1.09				
1,000	1.08				

It is seen that the magnetic dispersion is greater with the smaller sizes of machines, because the surfaces from which it occurs are relatively longer compared with the total flux. It is also greater with cast-iron magnets and pole-pieces and with smooth-core armatures.

It is theoretically possible to predetermine the dispersion of a given machine from the working drawings,† the calculations being based upon the principle that where a circuit offers alternative paths, the flux will divide itself between the paths in the proportion of their relative magnetic conductance or permeance. In fact, the theory of parallel electrical circuits is here applicable. Various rules have been devised for this purpose; but the manufacturers' designer usually contents himself with referring to tables such as that given above.

Exciting Ampere-Turns. The determination of the exciting ampere-turns for a machine is a simple matter if we know the dispersion coefficient and the magnetic properties (as shown by the B–H curve) of the materials forming parts of the magnetic circuit. See Fig. 112.

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* *Dynamo-Electric Machinery*, S. P. Thompson. New York, 1904, Vol. I, p. 138.

† *Dynamo-Electric Machines*, A. E. Wiener, 2d ed., p. 217.

The simplest mode of procedure is to fix approximately the flux necessary to pass through the armature in order to produce the required e. m. f.* Knowing this value, and also the size of the machine, we may select from Table II a suitable dispersion coefficient, and thus find the flux required to be produced by the field winding. That is:

$$\phi_m = \nu \, \phi_a$$

The next step is to allow a sufficient cross-section of material in the various parts to carry this flux at a reasonable flux-density. Knowing the latter at once fixes the reluctance, and the necessary number of ampere-turns is found by solving the equation connecting the flux, m. m. f., and reluctance of each portion of the circuit, given on page 10. That is,

$$\text{Ampere-turns} = I\,T = \frac{\phi\, l}{1.257\, A\mu} = \frac{B\, A\, l}{1.257\; A\,\mu} = \frac{B\, l}{1.257\;\mu}.$$

Where B is the flux-density per square centimeter, and l the length of the part in centimeters, the sum of the ampere-turns required for the different parts will then give the total ampere-turns for that circuit. The magnetic path from one pole to its neighbor of opposite polarity and return, is alone considered as indicated in Figs. 104, 105, 106 (assuming a ring-type yoke). Hence the total ampere-turns for this circuit will be those necessary per pair of poles. In other words, each field-coil must have one-half of this total value.

As average values for the magnetic densities in the various parts of continuous-current generators, we may take the figures of Table III, departures from which are, however, often necessitated by circumstances.

If the particular solution thus arrived at is not suited to the various conditions, a slight change in the original assumptions will bring one nearer to the proper value. In fact, the more preliminary calculations that are made, the more nearly perfect and the more reliable will be the final figures; furthermore, it is always wise to make assumptions both sides of the accepted value, to make sure that it is right.

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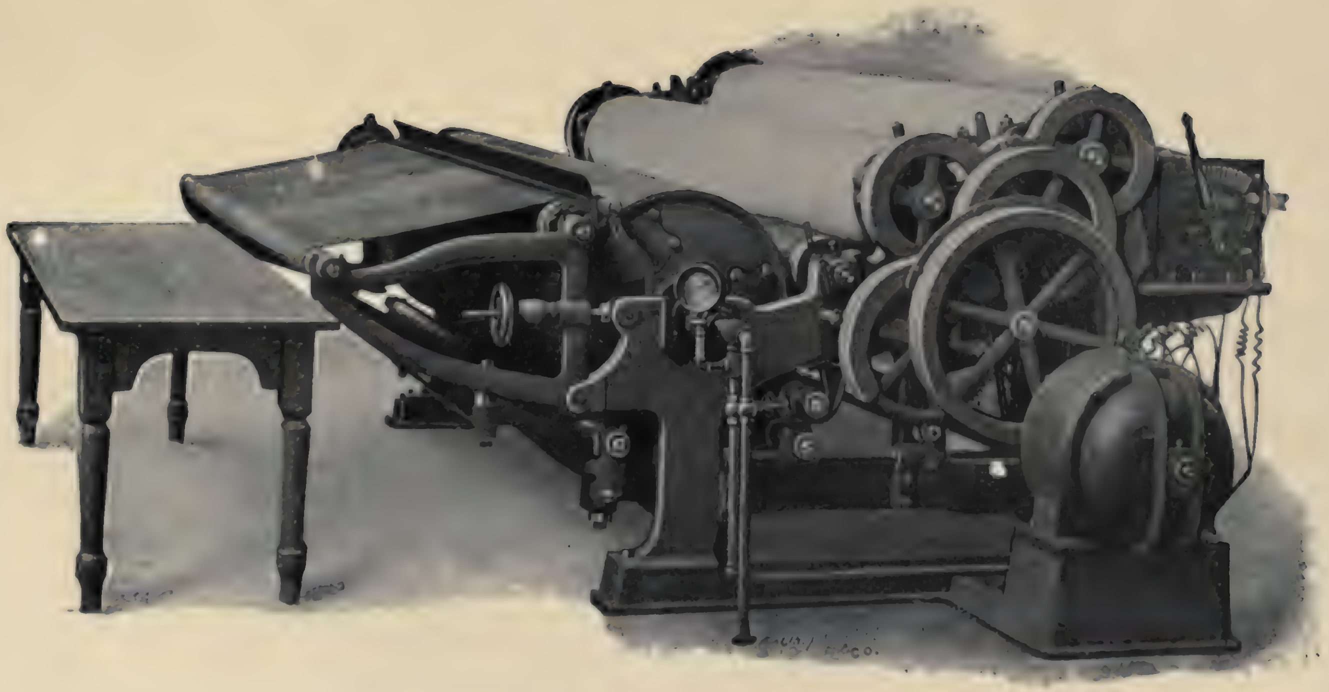
*See Equations 1 and 2, page 62.



FULLY ENCLOSED MOTOR

Driving Hercules Laundry Mangle.

Triumph Electric Company.

As these assumptions carry with them the selection of the magnetic dimensions of the machine, it will be well to consider these here.

TABLE III

Average Flux-Densities in Various Parts of Continuous-Current Generators

Flux-Density, in: —	Lines per Square Inch	Material
Armature body	50,000 to 95,000	Soft sheet iron or mild steel
Armature teeth	125,000	Do.
Air-gap	40,000 to 55,000	Air
Magnet-cores	75,000 to 100,000	Cast steel or wrought iron
Magnet-yoke	70,000 to 90,000	If cast steel or wrought iron
	35,000 to 50,000	If cast iron

(*a*) *Yoke.* In all machines of the ring (yoke) type, the yoke carries only one-half the total flux, as can be seen by reference to Figs. 104 to 106. The magnetic length is the mean length of path.

(*b*) *Magnet-Cores.* As each core carries the whole flux for one pole-face, the entire section of one core is considered. The length of the magnetic path in the magnet-cores is, however, twice the length of one core.

(*c*) *Air-Gap.* Since slotted armatures are the type used almost exclusively at present, the magnetic area of this portion will be equal to the pole-face area. The total magnetic length of these gaps is taken as twice the distance from iron to iron, measured perpendicular to the armature periphery.

(*d*) *Armature Core.* Here, also, the magnetic flux divides into two or a multiple of two paths (for the ring-yoke design), so that the magnetic area carries only one-half the flux entering the armature from one pole-face. The magnetic section is also less than the gross section, on account of the insulation of the core-discs* and the presence of ventilating ducts.† If the latter are absent, it is usual to allow 10 per cent as space loss if the insulation is varnish, and 15 per cent if it is paper. When the air-ducts are present, 25 per cent may be assumed for preliminary calculations with varnish insulation, and 35 per cent with paper insulation. The magnetic length is the length of the mean path lying between the roots of the teeth and the periphery of the internal hole.*

---

* See page 14 for reason for laminating and insulating core-discs.

† See page 171 for design, etc., of ventilating ducts.

(*e*) *Teeth.* The total length traversed by the flux in this portion of the circuit is equal to twice the depth of one tooth. The width of one tooth may be taken as the width at the root, the teeth being generally trapezoidal in shape. The number of teeth receiving the flux from one pole may be taken as the number lying immediately under the pole-face, *plus* one or two, depending upon the allowance for fringing.† The magnetic area of the teeth will therefore be the number so determined, *multiplied by* the product of the mean width of one tooth and the mean length of the armature, where the latter is the gross length *minus* the percentage allowed for insulation and air-ducts. Account must also be taken of the fact that when the teeth are operated at densities of 100,000 lines per square inch or more, part of the flux from the poles will take the alternative air-paths through the slots to the armature core, since at this high density their permeance is not insignificant compared with that of the teeth themselves. In other words, the ampere-turns calculated to force the flux through the teeth alone at high flux-densities would be in excess of the correct amount.

In order to find the true value of the flux-density in the teeth if we know the apparent flux-density, let us assume that:

$\propto$ = Ratio of net length to gross length of armature core;
B_t = True value of the tooth flux-density;
b_t = Width of a tooth, at the root;
b_s = Width of a slot;
h = Height or depth of a slot;
l = Net length of the armature parallel to the shaft;
ϕ_a = Flux entering the armature from one pole;
ϕ_t = Flux actually carried by the teeth, from one pole.

We then have:

$$\text{Iron section of one tooth} = b_t \times l.$$

$$\text{Air section of one slot} = \frac{b_s \times l}{\propto}.$$

The actual space forming an alternative path for the magnetic flux, per slot, will be given by the area of one slot (parallel to the pole-face) *plus* the area lost along one tooth by insulation and air-ducts; or,

---

* The "internal hole" is that portion of the armature between the center and inner edge of the core.

† "Fringing" means spreading of flux issuing from a pole-shoe.

$$\text{Section of air-space per slot} = \frac{b_s \times l}{\alpha} + (1 - \alpha)\frac{b_t \times l}{\alpha}$$

$$= \frac{l\,(b_t + b_s - \alpha\, b_t)}{\alpha}.$$

Since the flux entering the armature from one pole will divide between the two paths inversely as the reluctance of the two, we have, as the flux in the air-space,

$$(\phi_a - \phi_t) \propto \frac{l\,(b_t + b_s - \alpha\, b_t)}{\alpha\, h};$$

and the true flux in the teeth,

$$\phi_t \propto \frac{b_t\, l\, \mu}{h},$$

in which μ is the actual permeability of the teeth when transmitting the flux ϕ_t.

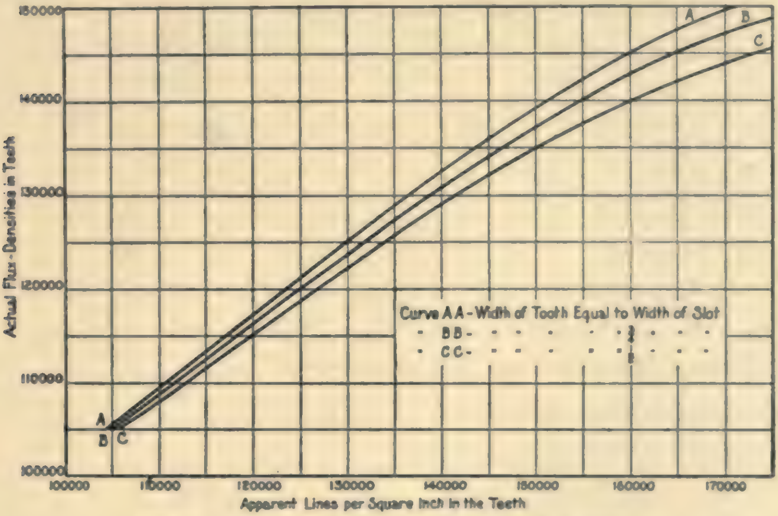


Fig. 109. Apparent and Actual Flux-Densities in Teeth.

Dividing the second equation by the first, we obtain,

$$\frac{\phi_t}{\phi_a - \phi_t} = \frac{\alpha\; b_t\; \mu}{b_t + b_s - \alpha\; b_t};$$

$$\phi_t\,(b_t + b_s - \alpha\, b_t + \alpha\, b_t\, \mu) = \phi_a\, \alpha\; b_t\, \mu$$

$$\frac{\phi_t}{\phi_a} = \frac{\alpha\, b_t\, \mu}{b_t + b_s - \alpha\; b_t + \alpha\; b_t\, \mu} = \frac{B_t}{B_a}.$$

Taking this last equation, and substituting for α 0.75 (a common value), and various ratios for $b_t \div b_s$, we obtain the curves given in Fig. 109, by assuming various values for B_t, finding the corresponding values of the permeability from Fig. 110, and then calculating B_a. If other values of α are used and greater accuracy is desired, where the actual B–H curve of the material of the teeth is known, these new quantities should be placed in the equation given above, and new curves drawn.

Example of Calculation. In order that the foregoing rules may be clearly understood, and to exemplify the use of the curves and the method of calculation, we shall take a concrete case of dynamo design. In Fig. 111 is given a dimensioned sketch of a modern six-pole continuous-current generator having a capacity of about 200 kw. Assuming that 12,500,000 lines are required to produce the rated e. m. f. in the armature, let us calculate the ampere-turns per pair of poles to produce this flux in the armature. From Table II, $\nu = 1.11$ approximately, and the data of the magnetic circuit around path A or path B is:

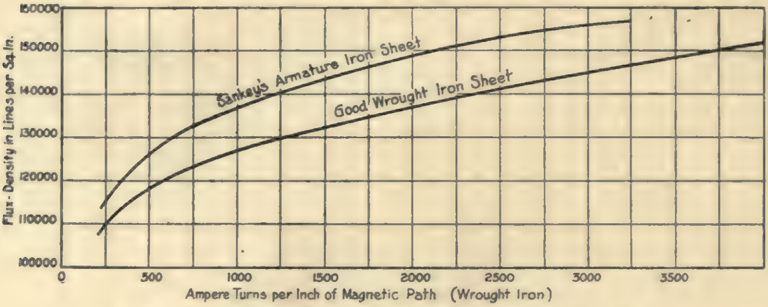


Fig. 110. Magnetization Curves at Very High Densities.

PART	MATERIAL	TOTAL FLUX
Yoke	Cast steel	6,937,500
Pole-cores	Cast steel	13,875,000
Pole-shoes	Cast steel	13,875,000
Air-gap	Air	12,500,000
Armature teeth	Sheet steel	12,500,000
Armature core	Sheet steel	6,250,000

We now estimate the magnetic lengths and areas as follows:

Yoke. From Table III, we assume the flux-density = 65,000; hence the cross-section of the yoke is

$$6,937,500 \div 65,000 = \text{approximately } 105 \text{ sq. in.} = A_y.$$

Consequently the dimensions of the yoke would be, say, 6 in. by 17.5 in., making the actual flux-density in the yoke,

$$B_y = 6,937,500 \div 105 = 65,200 \text{ lines per sq. in.}$$

The length of magnetic path, scaled off from the drawing, is

$$l_y = 55 \text{ in.}$$

Magnet-Cores. Assuming, from Table III, the flux-density in the teeth as 85,000 lines per sq. in., we have as the required area of cross-section of the magnet-cores,

$$13{,}875{,}000 \div 85{,}000 = 163.2 \text{ sq. in.}$$

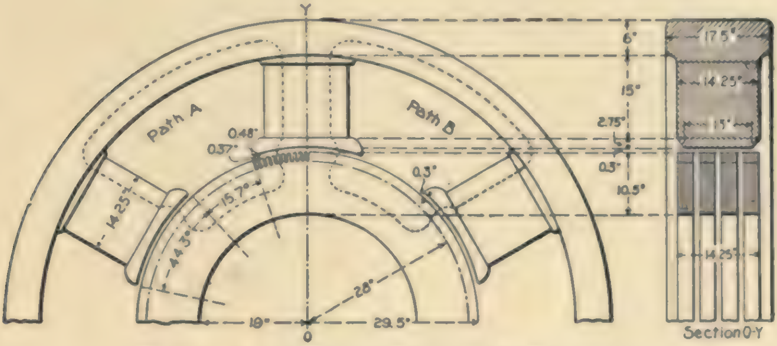


Fig. 111. Part of Magnetic Circuit of a Six-Pole Machine.

Selecting a circular section for the pole-cores, let us assume a diameter of, say, 14.25 inches, as giving an area of cross-section nearest to that above computed. This gives:

$$A_m = 159.5 \text{ sq. in., and}$$

$$B_m = \frac{13{,}875{,}000}{159.5} = 87{,}000 \text{ lines per sq. in.}$$

The length of magnetic path in the pole-cores is twice the length of one; so that,

$$l_m = 2 \times 15 = 30 \text{ in.}$$

Pole-Shoes. These are cast-steel extensions affixed to the magnet-cores to increase the air-gap area. The mean area of each shoe is,

$$A_s = 197.5 \text{ sq. in.;}$$

so that,

$$B_s = \frac{13{,}875{,}000}{197.5} = 70{,}400 \text{ lines per sq. in.}$$

The mean length of magnetic path per shoe is 2.75 in. Hence we have,

$$l_s = 2 \times 2.75 = 5.5 \text{ in.}$$

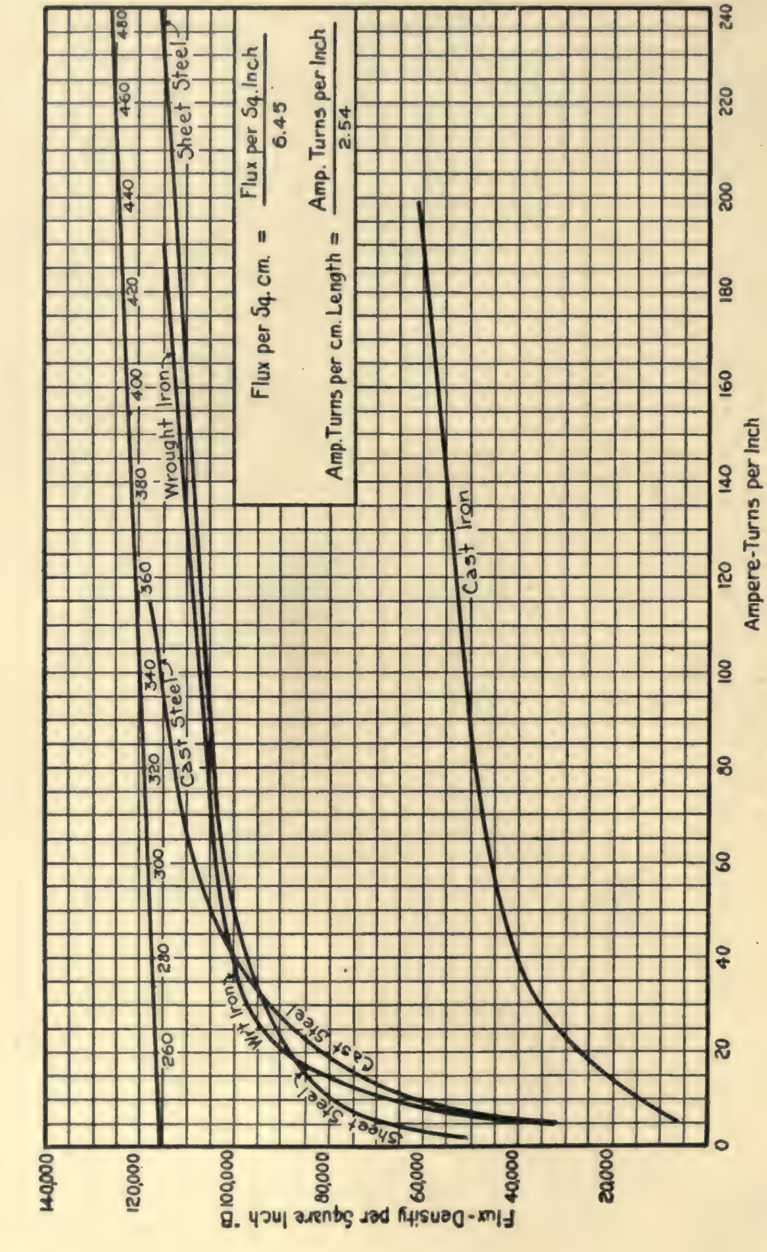


Fig. 112. Magnetization Curves of Irons and Steels.

Air-Gaps. The magnetic area of the air-gap being the area of the pole-face, we have it equal to 300 sq. in. Hence

$$B_g = 12{,}500{,}000 \div 300 = 41{,}700 \text{ lines per sq. in.}$$

The magnetic length through air in path *A* or *B* is twice the length of an air-gap; that is,

$$l_g = 2 \times 0.3 \text{ in.} = 0.6 \text{ in.}$$

Armature Teeth. The iron area of the 28 teeth acted upon by one pole, if the width of one tooth at its root is 0.326, is:

$$A_t = 0.326 \times 28 \times 14.25 \times 0.75 = 97.4 \text{ sq. in.}$$

Therefore,

$$B_t = \frac{12{,}500{,}000}{97.4} = 128{,}500 \text{ "apparent" lines per sq. in.}$$

Referring to Fig. 109, we see, since a tooth is as wide as a slot, that $B_t = 124{,}200$ actual lines per square inch in the teeth.

For the magnetic length, we have,

$$l_t = 2 \times 1.5 = 3.0 \text{ in}$$

Armature Core. The magnetic area is

$$A_c = 9 \times 14.25 \times 0.75 = 96.3 \text{ sq. in}$$

Hence,

$$B_c = \tfrac{1}{2} \times \frac{12{,}500{,}000}{96.3} = 65{,}000 \text{ lines per sq. in.,}$$

as the flux divides and takes two paths through the armature core.

The mean length of the magnetic path as obtained from the drawing, is:

$$l_c = 33 \text{ in.}$$

The preceding data may now be tabulated as follows:

PART	MATERIAL	MAGNETIC AREA IN SQ. IN.	B IN LINES PER SQ. IN.	LENGTH OF PATH IN IN.
Yoke	Cast Steel	105	65,200	55
Pole-core (1)	" "	159.5	87,000	15
Pole shoe (1)	" "	197.5	70,400	2.75
Air-gap (1)	Air	300	41,700	0.3
Arm. Teeth	Sheet steel	97.4	128,500	1.5
Arm. Core	" "	96.3	65,000	33

By reference to the magnetization curves (Fig. 112), the ampere-turns per inch of length for the various materials at the flux-densities determined may be found, and the ampere-turns for total length of path computed. The results may then be tabulated as follows:

PART	FLUX-DENSITY IN LINES PER SQ. IN.	AMPERE-TURNS PER IN. LENGTH OF MAGNETIC PATH	LENGTH OF PATH IN INCHES	AMPERE-TURNS FOR TOTAL PATH
Yoke	65,200	12	55¼	661
Pole-cores (2)	87,000	21.5	30	645
Pole-shoes (2)	70,400	13.5	5.5	75
Air-gaps (2)*	41,700	13,080	0.6	7,745
Arm. Teeth (2)	128,500	589	3	1,767
Arm. Core	65,000	8	33	264
		Ampere-turns per pair of poles,		11,157

Coil Winding Calculations. In series field-coils the whole of the external current, or a definite part of it, is used for the production of a m. m. f., so that the number of turns of wire or strip is found by dividing the requisite number of ampere-turns at any given load by this current. Furthermore, this wire or conductor must be of sufficient size to carry safely, efficiently, and without overheating, the given current. The series-wound generator is at present in general use for arc-lighting machines; and as the current in this case is usually about 10 amperes, it has been found by experience that, depending upon the depth of the winding, No. 10 or No. 8 B. & S. gauge wire are the correct sizes to use.

If the machine were to be separately excited, it is probable that the e. m. f. of the exciter would be specified, and we should have practically the shunt case. If, however, the current were given, the determination would be the same as in the case of the series winding above.

Shunt Winding Calculations. The determination of the best size of wire for a shunt winding is far more difficult than for a series one, in that merely the ampere-turns and the voltage applied to the terminals of the coil are given, while the space allotted to the winding and the heating limits must be kept within definite bounds. Various methods have been suggested, but none are very satisfactory. One of the simplest is as follows: The temperature of the field coils for

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*In computing ampere-turns per inch length of the air-gap, it must be remembered that for air $\mu = 1$; so that in inch-units we have,

$$IT_g = 0.3133 \times B_g \times l_g\,.$$

The number 0.3183 is called the *gap-coefficient*, and represents the number of ampere-turns per inch length of path, requisite for a flux-density of one line per square inch in air.

continuous operation at rated load may be assumed to be 75° C.—that is, a 50° C. rise above a room temperature of 25° C. At this temperature the resistance of a mil-foot of copper wire (that is, a wire one foot long and 0.001 inch in diameter) is 12.56 ohms. Hence,

$$R = \frac{12.56 \times l}{\text{Circ. mils}},$$

in which l is the length of the conductor in feet, and "Circ. mils" is the area of cross-section in circular mils, which is equal to the diameter in mils squared. The current traversing the wire when a voltage V' is applied at its terminals, is,

$$I = \frac{V' \times \text{Circ. mils}}{12.56 \times l}.$$

It is also evident that the ampere-turns in any winding are numerically equal to the amperes that would result if a single turn of wire were supposed to be subjected to the given voltage, because two turns would have twice the resistance and would take one-half the current; and so on for any number. Hence,

$$\text{Ampere-turns} = \frac{V' \times \text{Circ. mils}}{12.56 \times l},$$

in which l represents the mean length of one turn in feet. By transposition we obtain the cross-section of the wire required—that is:

$$\text{Circ. mils} = \frac{\text{Ampere-turns} \times l \times 12.56}{V'}.$$

Example. An 8-pole 150 kw. shunt generator required 808 ampere-turns per pair of poles when its terminal voltage was 115. The poles were 9½ inches wide, and 10 inches long parallel to the shaft. Allowing a depth of winding of about 2 inches and a spool thickness of about ½ inch, the mean length of one turn would be nearly 50.5 inches, the poles being rectangular. Then, at rated voltage, V' per pair of field-exciting coils is 115 ÷ 4 = 28.75 volts, and we have:

$$\text{Circ. mils} = \frac{808 \times 50.5 \times 12.56}{28.75} = 17{,}850.$$

Referring to a wire-gauge table, we see that the wire having an area of cross-section in circular mils nearest this figure is No. 7 B. & S., for which circ. mils = 20,820.

In applying the above formula to the shunt winding for a dynamo, allowance must be made for the resistance of the rheostat which is usually put in the shunt circuit to regulate the e. m. f.

This resistance will consume from 20 to 30 per cent of the no-load voltage; and the value of V' to be substituted in the formula should therefore be a corresponding amount lower, unless the rated load voltage be used. In this case the resistance of the rheostat is determined by the resistance which it is necessary to add to that of the field-winding in order to keep the generated e. m. f. at the proper point for all other loads.

Space-Factor. In all cases where insulated conductors, whether strip or wire, are used, the space taken up by the conductor proper is always a fraction of the whole space occupied by the entire winding. This fraction will obviously depend upon the shapes of the conductors and the space set apart for the winding, and also upon the thickness of the insulation. The ratio of net cross-sectional area of copper in any such space to the gross section, is called the *space-factor*.

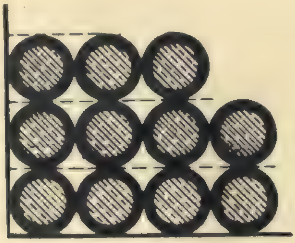


Fig. 113. Square Order of Bedding.

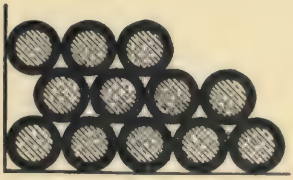


Fig. 114. Hexagonal Order of Bedding.

In winding bobbins for field-magnet coils, the space-factor depends largely upon whether square or round wire is used. If the former, the space wasted is less, and the heating of the coil is reduced (for a given number of turns carrying a given current, etc.), since there is less cross-section filled with air or insulation, either of which is a bad conductor of heat. If round wires are used (as is generally the practice), the space-factor will be determined chiefly by the ratio between the relative thicknesses of the wire and its insulation, and also by the partial bedding of one layer of wires between those of the layer below.

Suppose the round wires to be wound so as to lie in the square order without any bedding, as in Fig. 113. Then, if the diameter of the bare wire is d, and the insulated diameter is d_1, the ideal space-factor would be:

$$\sigma = 0.7854 \frac{d^2}{d_1^2}, \qquad \text{(21)}$$

because the area of each small circle is $\pi \frac{d^2}{4} = 0.7854\ d^2$, and the area of the small square enclosing each outer circle is d_1^2. Suppose, however, an extreme case of bedding, as in Fig. 114, where the wires lie in hexagonal order. By similar reasoning, the space-factor would then be:

$$\sigma = 0.906 \frac{d^2}{d_1^2}.$$

If rectangular strip is used, there is no bedding, and no wasted space except where the end of one layer of a coil extends to the layer above. If the area of cross-section of the bare conductor is *ab*, and the area of the same, insulated, is *a′ b′*, the space-factor is simply *ab* ÷ *a′ b′*. In practice it has been found that edge-wound strip gives the highest space-factor, ranging from 0.83 to 0.93.

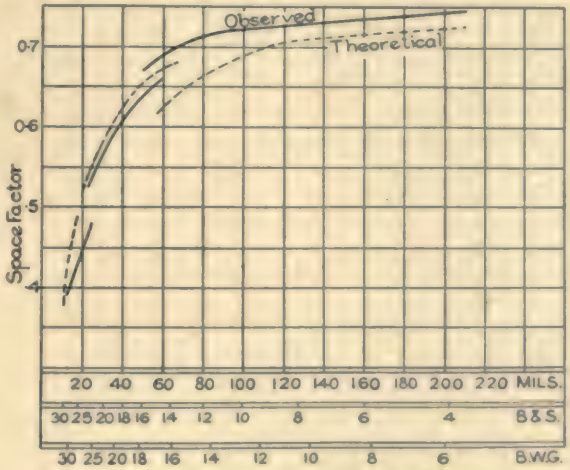


Fig. 115. Curves Showing Space-Factors for Round Wires of Various Gauges.

In practice, with round wires, it is found, however, that even the most experienced winders produce a bedding of seldom over 3 per cent; so that the safest course is to assume no bedding, and to take the space factor as given above unless it is actually known.

Some actual figures have been put into graphical form by Dr. S. S. Wheeler, and these are given in Fig. 115. Here the full lines represent the values by the formula assuming the square order; and the broken lines, the observed values. It is seen that the larger sizes of wire do actually bed a little, while with smaller sizes the bedding is negative.

Connections of Exciting Coils. It is the almost invariable custom to connect all the field-magnet exciting coils of the same type in series with each other, so that the magnetizing current is the same throughout. Then, if the number of turns per spool is the same, the flux per pole will be uniform. They must also be connected up so as to produce alternate north and south poles, so that if all the coils are wound in the same direction, and similarly placed, the connections will come alternately at the yoke-end and the pole-face end of the bobbin, as in Fig. 116.

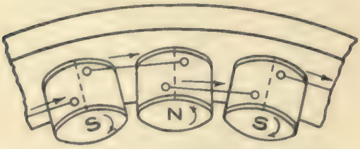


Fig. 116. Connections of Field-Magnet Coils.

Excitation Losses. Having computed the resistance of the shunt winding (r_{sh}) by the previously explained method, we have $\frac{V}{r_{sh}} \times V = \frac{V^2}{r_{sh}}$ as the watts actually expended in the shunt field-coils, V being the terminal voltage of the generator. To this loss must be added the one in the shunt-regulating resistance, and also the loss in the series-regulating coils, if any, in order to give the total watts required in excitation. For shunt-wound machines, the watts required in excitation vary in practice from 1 to 8 per cent or more of the output, depending upon the capacity of the machine. As a guide in this direction, Table IV has been constructed, giving the *maximum permissible* excitation losses.

TABLE IV

Excitation Losses

Output of Machine in Kilowatts	Excitation Losses in per cent of Rated Load Output
5	6
10	5
20	4
30	3.5
50	3.0
100	2.75
200	2.50
300	2.25
500	2.00
1,000	1.75
2,000	1.50

Heating of Magnet-Coils. The heat developed in field-magnet coils is dissipated in two ways: It is either carried by conduction through the copper and the insulation, and then by radiation and convection to the outer air, or it is conducted to the iron portions of the machine nearby and radiated off by these. In either case the amount of heat produced in the coil is equal, in watts, to the product of the resistance and the square of the current, while the rate at which the heat is lost cannot be very accurately calculated.

In order to compute the temperature which a field-coil finally reaches, let w_m = watts wasted in field-coils at rated load of machine;

A'_m = Radiating area of all the bobbins, in square inches:

θ_m = Final temperature rise above surrounding air (usually 50° C.).

Then

$$\theta_m \propto w_m,$$

$$\theta_m \propto \frac{1}{A'_m}.$$

So that,

$$\theta_m \propto \frac{w_m}{A'_m};$$

or,

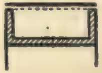
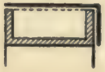
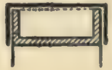
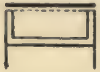
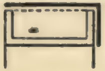
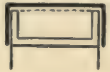
$$\theta_m = h\frac{w_m}{A'_m},$$

where h is a constant depending upon the depth of the winding, upon the cooling action due to the armature rotation, and upon the condition of the surrounding air. It is the temperature above that of the sorrounding air to which the coil would be raised if radiating 1 watt per square inch.

Experience has shown that a certain rise in temperature is allowable, this being usually put at 50° C. or 90° F. above the temperature of the surrounding air. Tests have also demonstrated that this rise in temperature is not usually exceeded if a certain surface of coil is allowed for each watt converted into heat. The difficulty in fixing this is due to the way in which the heat is dissipated, as before noted. Also, authorities differ in regard to what surface shall be considered as radiating, in some cases going so far as to count only the external cylindrical surface of the coil. As a matter of fact, the internal surface of the coil, next to the poles, usually dissipates more heat in a given time than the external surface, so that the total area should be reckoned. This may be done by assuming a proper

TABLE V

Specific Temperature Increase in Magnet-Coils of Various Proportions at Unit Energy Loss per Sq. In. of Core Surface

CYLINDRICAL MAGNETS								RECTANGULAR AND OVAL MAGNETS	
Ratio of Winding Depth to Core Diameter	Winding Depth in Parts of Core Diameter	Ratio of External Coil Surface to Core Surface 	Ratio of Cylindrical Surface plus One End Surface of Coil to Core Surface 	Ratio of Cylindrical Surface and Both End Surfaces of Coil to Core Surface 	Increase of Magnet Temperature for Each Watt per Square Inch of Core Surface			Ratio of Radiating Surface to Core Surface	Temperature Increase for Unit Energy Dissipation
					Radiating Surface Consisting of				
					Cylindrical Coil Surface 	Cylindrical Surface plus One End Surface 	Cylindrical Surface and Both End Flanges 		
1 : 100	.01	1.02	1.03 to 1.05	1.04 to 1.07	75°	74° to 72°	73° to 71°	1.02	75°
1 : 50	.02	1.04	1.05 " 1.10	1.07 " 1.12	73	72 " 69	71 " 68	1.05	72
1 : 30	.033	1.067	1.07 " 1.15	1.10 " 1.20	71	70 " 65	69 " 63	1.1	69
1 : 20	.05	1.1	1.12 " 1.20	1.15 " 1.30	69	68 " 63	65 " 58	1.25	60
1 : 15	.067	1.133	1.15 " 1.25	1.20 " 1.40	67	65 " 60	63 " 53.5	1.5	50
1 : 12	.083	1.167	1.20 " 1.30	1.25 " 1.45	65	63 " 58	60 " 51.5	1.75	43
1 : 10	.1	1.2	1.25 " 1.40	1.30 " 1.55	63	60 " 53.5	58 " 48	2	37.5
1 : 9	.11	1.22	1.28 " 1.45	1.35 " 1.60	61.5	59 " 51.5	55.5 " 47	2.25	33
1 : 8	.125	1.25	1.30 " 1.50	1.40 " 1.70	60	58 " 50	53.5 " 44	2.5	30
1 : 7	.143	1.286	1.35 " 1.55	1.45 " 1.80	58.5	55.5 " 48.5	51.5 " 41.5	3	25
1 : 6	.167	1.33	1.40 " 1.60	1.50 " 1.90	56.5	53.5 " 39.5	50 " 39.5	3.5	21.5
1 : 5	.2	1.4	1.50 " 1.75	1.60 " 2	53.5	50 " 43	47 " 37.5	4	19
1 : 4	.25	1.5	1.65 " 2	1.80 " 2.5	50	45.5 " 37.5	41.5 " 30	5	15
1 : 3	.33	1.67	1.85 " 2.5	2 " 3	45	40.5 " 30	37.5 " 25	6	12.5
1 : 2	.5	2	2.25 " 3	2.5 " 4	37.5	33 " 19	30 " 19	8	9.5
1 : 1	1	3	3.5 " 5.5	4 " 8	25	21.5 " 13.5	19 " 9.5	10	7.5
3 : 2	1.5	4	5 " 8.5	6 "12	19	15 " 9	12.5 " 6	12	6
2 : 1	2	5	6.5 "12	8 "18	15	11.5 " 6	9.5 " 4	15	5

value of *h*, which, according to W. B. Esson, is about 55 and according to Esterline 83, for ordinary bobbins; or by relying upon the experimental results given in Table V. Esson, in using this figure, counts as radiating surface only the external heat-radiating area, and not the end flanges and internal surfaces. Esterline includes in the radiating surface the external and internal areas and the flanges, counting the last two as radiating only one-half as much as a corresponding external area.

ARMATURE WINDINGS

Armature conductors—or *inductors*, as they are sometimes called—are almost universally made of copper. Their arrangement upon the armature, and the order in which they are connected together to form a complete winding, constitute one of the most involved subjects in the design of dynamo-electric machinery.

Classification. Armature windings may be classified according to the way the conductors are placed upon the armature core, as follows:

Ring Windings, in which the conductors are placed upon a ring-shaped core, passing through the interior of the ring in the form of a helix, and hence sometimes called *helical windings*.

Drum windings, having the conductors wound entirely upon the surface, or in slots upon the surface, of a cylindrical core.

Disc windings, where the conductors are arranged in a plane like the spokes of a wheel, the connections being similar to those in drum armatures.

Of all these types, the drum is almost exclusively used at the present time for the armature windings of continuous-current machines, since, in contradistinction to the ring winding, there are no internal return conductors to increase the amount of armature copper needed, and for the greater reason that formed coils are applicable, greatly reducing the first cost and facilitating insulation and repairs. A drum armature partly wound with formed coils is illustrated in Fig. 117.

Besides this grouping, we may also divide windings into *closed-coil* and *open-coil* types, depending upon whether the winding constitutes a closed or an open circuit. Closed-coil armatures are in almost general use for direct-current machines, since they give a steadier current and spark considerably less than the open-coil type.

The latter are used for direct-current arc-lighting machines and for star-wound alternators.

Armature Coil.—*Element of Winding.* A *winding element, section,* or *coil* is that portion of an armature winding which terminates at two commutator bars. In its simplest form it consists of two armature conductors (in drum windings), with the necessary end connections, so that the maximum number of armature coils is equal to one-half the number of armature conductors. In ring windings, an element may consist of only one armature conductor, the internal return portion being inactive (that is, cutting no flux) and therefore serving as an end connector. Such an element may also consist of 2 or $2n$ armature conductors in series for drum windings, or of n armature conductors in series for ring windings, where n is an integer; but this affects only the e. m. f. generated by the coil, the end connections of the section as a unit remaining unchanged. Similarly, the resistance of an element may be reduced by connecting several conductors in parallel; but this also does not affect the end connections of the coil as an element of winding; it merely increases the current-carrying capacity. In either case the *method* of winding

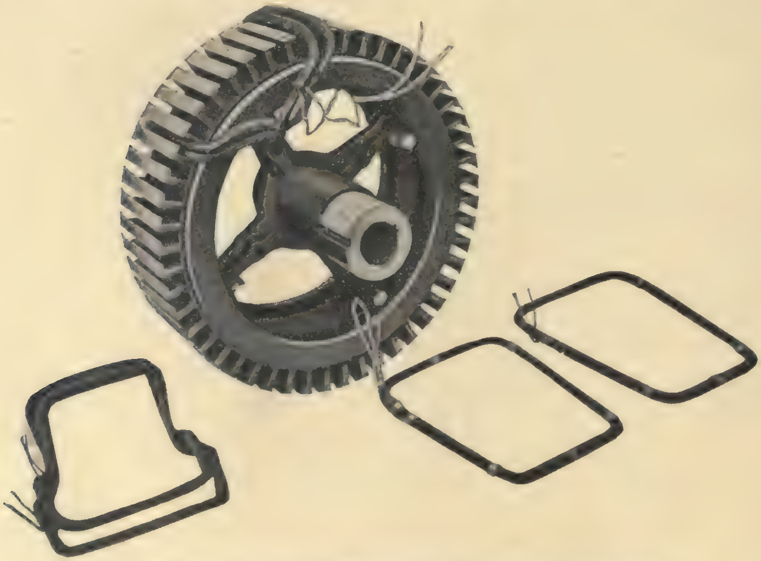
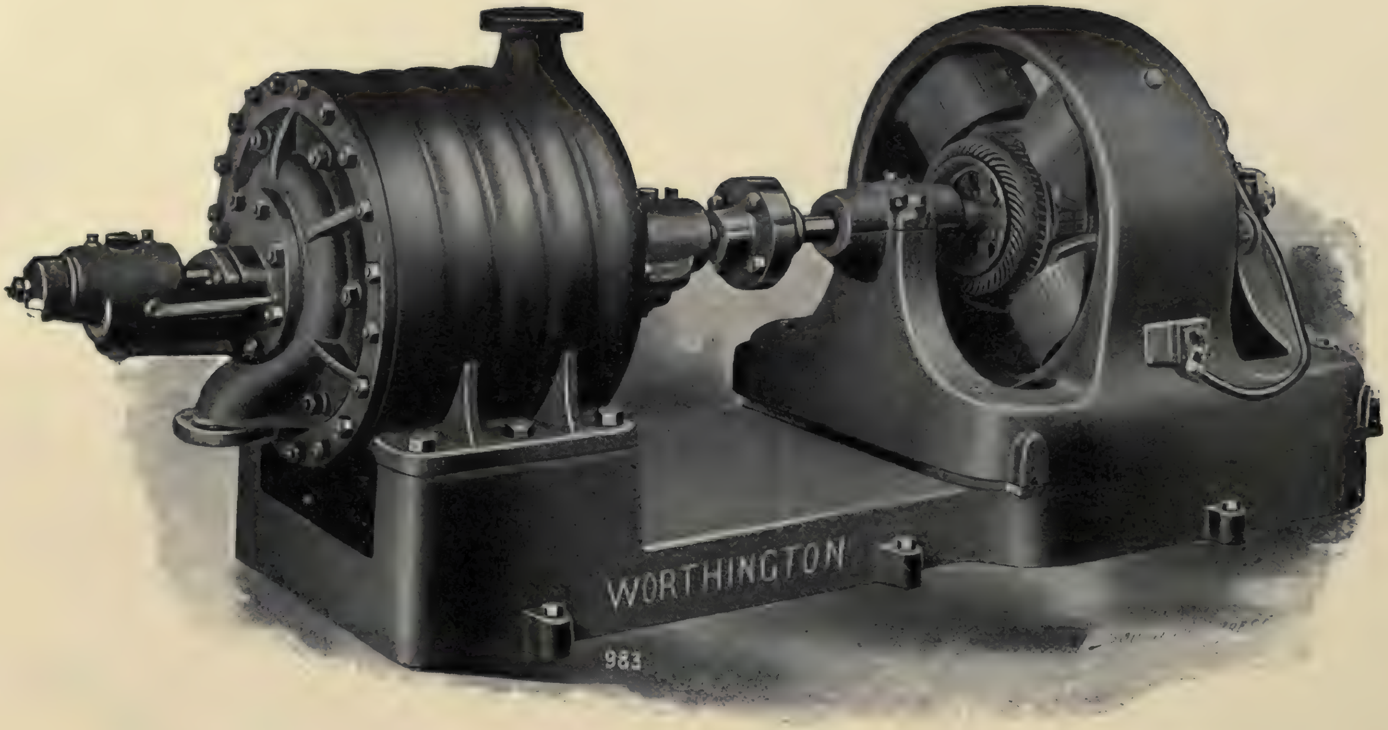


Fig. 117. Showing Method of Winding and Applying Formed Coils for an Armature Core.



FIVE-STAGE MOTOR-DRIVEN TURBINE PUMP.

Adapted to Heads up to 750 Feet.

is not altered by putting more turns of wire in series or in parallel in each section.

The whole theory of armature winding may therefore be said to resolve itself into a study of end connections; and in discussing drum windings, we shall consider an element consisting of two armature conductors with their end connections only.

Possible Number of Commutator Bars. We have seen that at each end of a section of winding there is a commutator bar. In the simplest form of ring-wound armature, each element of the winding contains only one armature conductor, so that the maximum number of commutator bars is Z, the rest of each element being equivalent to an end connection. The number of commutator bars in a ring winding may also be less than Z (where $Z =$ the number of armature conductors); but in any case it is $\frac{Z}{m}$, where m is 1 or an integer factor of Z.

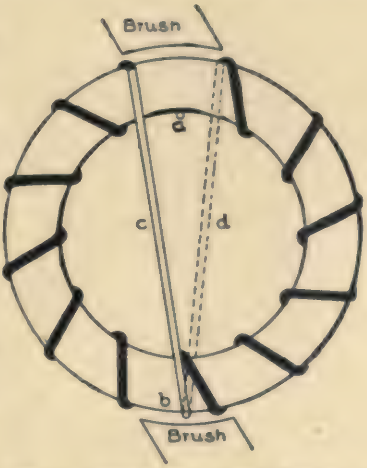


Fig. 118. Modification of Ring Winding to Form a Drum Winding.

In closed-coil drum windings, K, the number of commutator bars, has for its maximum value $\frac{Z}{2}$, and it may be $\frac{Z}{2m}$, for a drum-wound armature cannot have adjacent conductors connected to separate commutator segments and be a closed-coil winding. If each alternate armature conductor in a drum winding be considered as the return of its neighbor, the equivalent ring winding would be as indicated by coil in Fig. 118, and we then see that the armature would be short-circuited.

Field Step. In ring windings, the coils are wound around the armature core, so that they pass through its interior; but in drum windings the armature conductors are laid in slots on the surface of the core, and do not pass through the interior. It is plain, in the latter case, that unless one of the conductors of a section is cutting flux under a south pole at the same time that the other armature conductor of the same section is cutting flux under a north pole, either the coil will not be working at maximum efficiency (in which case only one conductor will be cutting flux), or both armature conductors will be under poles of like polarity at the same instant so that the e. m. f. generated in one will tend to equalize that in the other. Hence, in practice, we have one conductor of an element under a south pole at the instant that the other is under a north pole, in which case the e. m. f.'s generated by the two coils are additive. It is also universal to have the step or spacing from one armature conductor to the next of that section, nearly equal to the distance between the centers of adjacent unlike poles; but windings could be devised in which the step so made from one conductor to the next would be to the region of a more distant pole; in that case, however, the end connections would be unduly long.

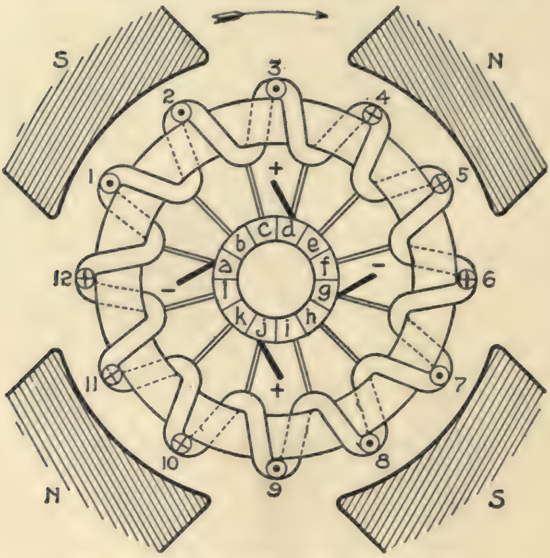


Fig. 119. Ring Winding for 4-Pole Machine.

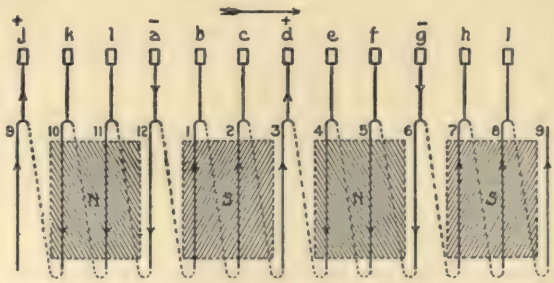


Fig. 120. Development of Ring Winding for 4-Pole Machine.

Pitch of Winding. The pitch or spacing of a winding denotes the distance from one inductor of the winding to the next inductor in the succession; and it is usual to express it in terms of the number of inductors spanned over. In order to see more clearly what

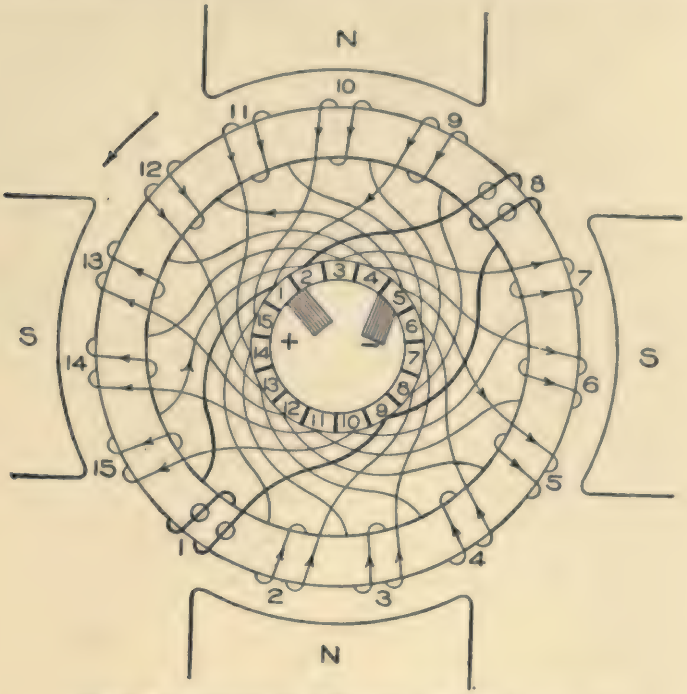


Fig. 121. Series-Connected Wave-Wound Ring Armature.

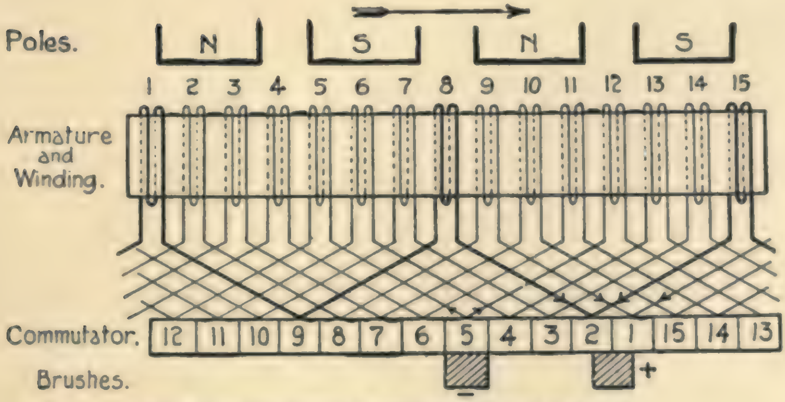


Fig. 122. Development of Winding Shown in Fig. 121.

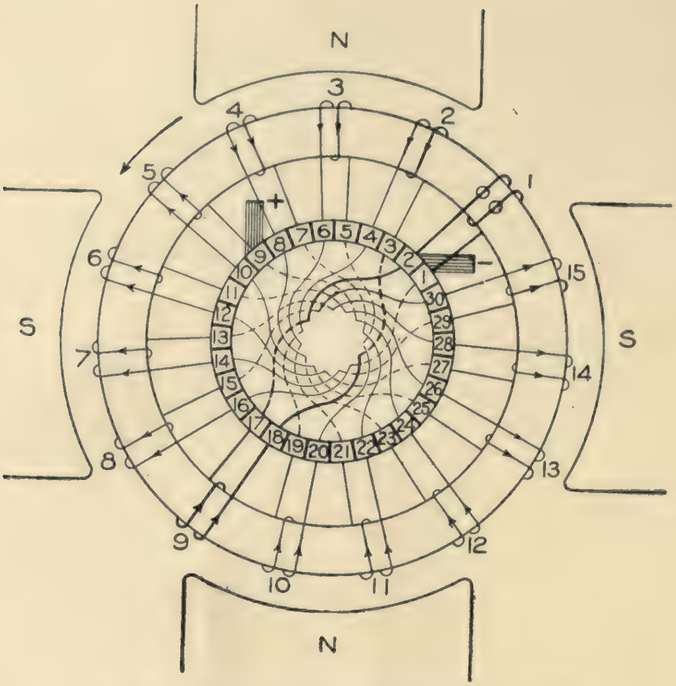


Fig. 123. Series-Connected Multipolar Ring Armature.

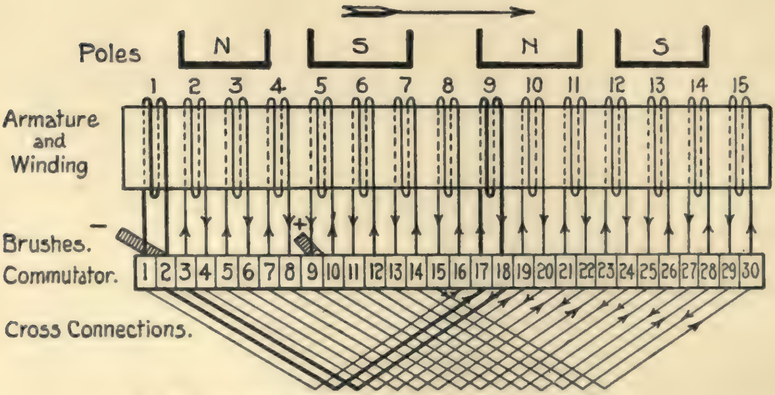


Fig. 124. Development of Winding Shown in Fig. 123.

is meant, let us suppose that the inductors around a certain drum winding are numbered consecutively from 1 up. If it is further assumed that inductor 1 is joined at the front end to inductor 16 to form a loop, and that 16 is joined at the rear to 31 to form a similar loop, the pitch at both ends would be 15. Had 1 been joined to 18 at the front end, and 18 to 3 at the rear end, then 3 to 19 at the front end, the front pitch would be $y_f = +17$, the back pitch $y_b = -15$, the average pitch 16, and the resultant pitch 2.

Ring Windings. Ring windings may be divided into two classes; the *spirally wound* ring, shown in Figs. 119 and 120, and the *series-connected wave-wound* ring, shown in Figs. 121, 122, 123, and 124 for two methods.

The first type, forming in itself a single closed helix, is unaffected by the number of poles; by merely placing $2p$ sets of brushes on the surface of the commutator at equal distances apart, the winding is at once divided into as many equal and symmetrical paths through the armature, and we have $c = p$. A multipolar armature is thus obtained, having as many parallel circuits and as many points of collection of the current as there are poles. The equation of the e. m. f. of such a *multipolar parallel-wound* or *multiple-circuit* armature is similar to that for a bipolar machine; that is,

$$E = \frac{Z \times p\,\phi \times \text{r. p. m.}}{60 \times 10^8 \times c} = \frac{Z \times \phi \times \text{r. p. m.}}{60 \times 10^8},$$

since $c = p$. This multipolar winding has greater current-carrying capacity than the bipolar, since there are more paths in parallel, the multipolar winding being therefore equivalent to several bipolar dynamos in parallel, just as the bipolar machine was shown to be equivalent to two sets of cells in parallel (Fig. 48).

As in a bipolar machine, there are two points on the commutator where the e. m. f. is zero—*i.e.*, where proper commutation may occur—so there will be p points in a multipolar parallel-connected ring winding where the current is commutated, and p brushes will be needed. If, however, the increased number of points of collection be regarded as a disadvantage, they may again be reduced to two, by joining all commutator bars which are situated $360 \div \frac{p}{2}$ degrees apart, so that sectors which are at any moment at the same voltage are connected together. Thus, in a four-pole machine, each commutator bar must be connected to that which is diametrically opposite, and there is a choice between two positions for the brushes at right angles to one another. In a six-pole machine, each cross-connection must unite three sectors situated 120° apart, and the brushes may be either 60° or 180° apart; in an eight-pole machine, four sectors 90° apart must be joined, and the brushes may be either 45° or 135° apart. Thus we see that in general the angle between the brushes of unlike sign may be $180° \div \frac{p}{2}$ or any uneven multiple of this angle. The commutator connections for a four-pole cross-connected winding of the type described, are shown in Fig. 125, while Fig. 126 illustrates the same for a six-pole machine. When thus cross-connected, the commutator must be made $p \div 2$ times as long as before, in order to provide sufficient surface of contact to collect the current by the two sets of brushes; also, the number of commutator segments must be divisible by p.

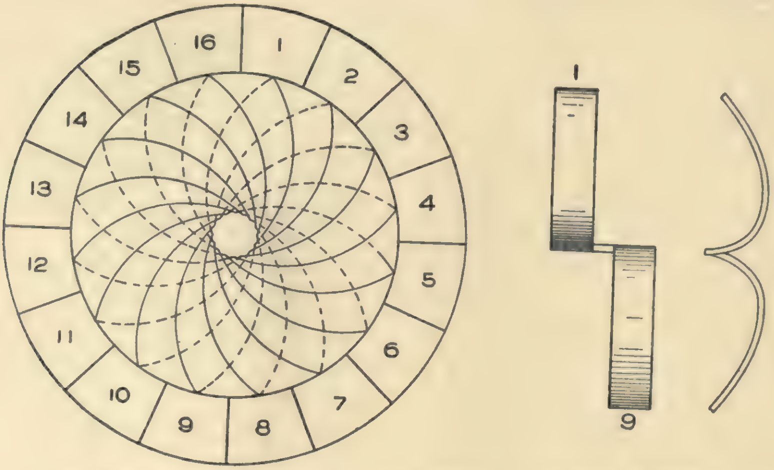


Fig. 125. Commutator Connections for a 4-Pole Cross-Connected Winding.

In the multipolar ring winding of Fig. 119, each pole corresponded to one circuit through the armature, the total number of circuits being therefore equal to the number of poles. It is also possible to add together the inductive effects of two or more poles, so that the e. m. f.'s produced by one-half the inductors on the armature are summed up in series. The winding will then have two paths in parallel, whatever the number of poles. This is called a *series-wound* or *two-circuit* armature. Ring windings of this kind are not used in practice, so that they need not be further considered. Series-wound or two-circuit drum windings are of practical importance, and will be described later.

Forms of Drum Windings. Closed-coil drum windings are of two forms, known as *lap windings* and *wave windings* respectively, and so called from the manner of connecting the ends of the inductors to form a section. In the bipolar type, there is no essential difference between the two forms; but when applied to multipolar machines, the divergence is marked.

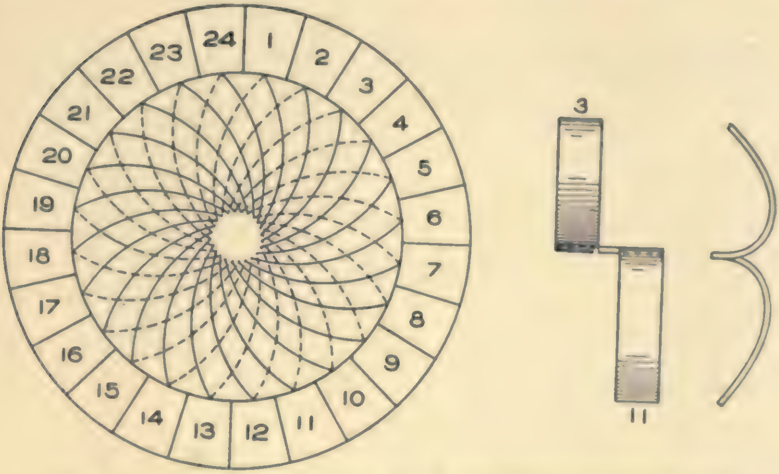
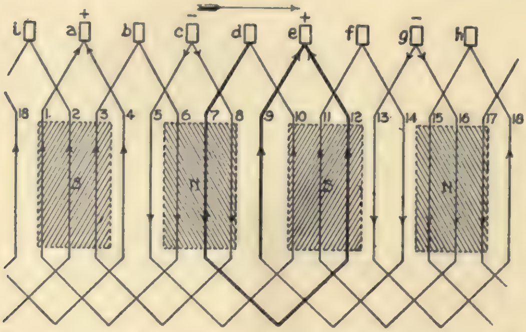


Fig. 126. Commutator Connections for a 6-Pole Cross-Connected Winding.

A simple (simplex) lap winding, Fig. 127, gives as many circuits through the armature as there are poles, whence it is similar to a parallel-wound ring armature. On the other hand, a simplex wave winding, Fig. 128, always gives 2 paths through the armature, irrespective of the number of poles.

It is seen, therefore, from the fundamental formula for the e. m. f. of a dynamo (page 62), that, for a given number of armature inductors, a wave winding will give more voltage than a lap winding in a multipolar field. The latter, however, will give a greater number of paths in parallel through the armature, thus increasing its current capacity.

The distinction between the two windings arises in the following manner. Since the inductors that are passing a north pole generate an e. m. f. in one direction, and those passing a south pole are generating an e. m. f. in the opposite direction, it is clear that an inductor in one of these groups should be connected to one in a nearly corresponding position in one of the other groups, so that the current may flow down one and up the other in agreement with the directions of the e. m. f.'s. If, now, we examine Fig. 127, we see that at the back of the armature—that is, the end distant from the commutator—each inductor is connected with the one five spaces further on, or the pitch at the back is 5. At the front end of the winding, after winding one element—as, for instance, *e*–9–14–*f*—a second element *f*–11–16–*g* is formed, which laps over the first; and so on completely around the winding. In the wave winding illustrated in Fig. 128, however, the case is different. The connections at the rear end remain as in the preceding winding; but at the commutator end, instead of lapping back toward the point from which it started, the connection turns the other way—as, for example, *c*–5–10–*h*. This results in a winding that advances in a sort of zigzag path; hence its name.



F	B		F
+ a	1	6	b
b	3	8	c
− c	5	10	d
d	7	12	e
+ e	9	14	f
f	11	16	g
− g	13	18	h
h	15	2	i
i	17	4	a

Fig. 127. Typical Simplex Lap Winding, and Winding Table for Same.

Lap Windings. Fig. 127 illustrates a simplex or single lap winding, since the terminals of an element are connected to adjacent commutator bars. Following through this winding and starting at segment *a*, we pass along conductor 1 to the rear of the armature, then by an end connection skip over to conductor 6, which leads to commutator bar *b*. From that point, conductor 3 leads again to the rear, and is there connected to 8, which brings us back to bar *c*. Following on in this manner to bar *i* by conductor 2, and from here *via* conductor 17, we finally reach bar *a* through 4, thus closing the winding on itself without traversing each conductor more than once. Calling the interval between the conductors connected at the rear of the armature the *back pitch* (y_b), and the interval between those connected together at the front end the *front pitch* (y_f), we see that for this winding, $y_b = +5$; and $y_f = -3$. The average pitch, being half the arithmetical sum of the front and back pitches, is $y_{av} = 4$; while the resultant pitch is $y_r = +2$, being the algebraic sum of the front and back pitches.

Considering only the case in which each element or section of the winding is a single loop, the number of such sections will be Z ÷ 2; the number of sections (which is the same as the number of resultant steps if multiplied by the length of each resultant step) will equal the total travel of the winding. This will be equal to *Z* if the whole winding must be traversed before closing upon itself. If, however, only one-half or one-third of the winding had to be traversed before the start was reached, the total travel would be *U*Z, where *U* is the number of times the winding must be traversed before finally closing on itself. We have, therefore, for the first condition controlling a lap winding,

$$\frac{Z}{2}(y_b + y_f) = U\,Z;\ \text{so that}\ U = \frac{y_b + y_f}{2},$$

where *U* may be any whole number. Hence it follows that the sum of the front and back pitches must in every case be an even number.

There is also the condition that no conductor shall be encountered twice; that is, no number of steps whatever, however often repeated, shall make $y_b + y_f$ equal to y_f. Or, taking *m* as any whole number,

$$y_f \gtrless m\,(y_f + y_b);$$

whence,

$$y_f \div y_b \gtrless m \div (1-m).$$

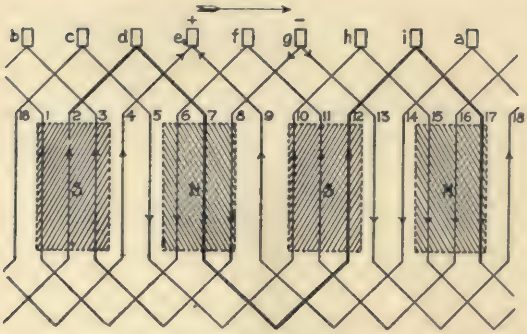
It follows from this inequality, that y_f and y_b cannot possibly have any common factor; and as their difference must be even, it is evident that both must be odd numbers. Also, to make the winding lap back, it is necessary that one of them should be a negative number.

Wave Windings. The winding illustrated in Fig. 128 is called a *simplex wave winding*. Starting at bar *a*, we pass along conductor 1 to the back of the armature, thence by a connector to conductor 6, and then ahead to bar *f*. From here we follow along conductor 11, and then 16 to *b*, whence we are led along 3 and 8 to *g*. Following through the complete winding, we arrive at bar *a* by way of conductor 14, after having traversed each conductor once. Thus the winding closes upon itself after passing through $p \div 2$ winding elements.

For this winding, then, we have,

$$y_f = +5; \; y_b = +5; \; y_{av} = 5; \; y_r = +10.$$

The resultant step is $y_f + y_b$ as before; and the number of such



F		B	F
a	1	6	f
f	11	16	b
b	3	8	g
− g	13	18	c
c	5	10	h
h	15	2	d
d	7	12	i
i	17	4	e
+ e	9	14	a

Fig. 128. Typical Simplex Wave Winding, and Winding Table for Same.

steps being $Z \div 2$, and the total travel through the winding being U, we have;

$$\frac{Z}{2}(y_f + y_b) = U Z; \quad \text{whence} \quad U = \frac{y_f + y_b}{2}.$$

In order that no conductor be encountered twice in traversing the winding, it must not be possible, by any number of repetitions of the step $y_f + y_b$, to recur to the step y_f beyond any previous number of repetitions of the resultant step. Hence, if m and n are any whole numbers, $m\,(y_f + y_b)$ must not equal $n\,(y_f + y_b)$ steps plus y_f. That is,

$$m\,(y_f + y_b) \gtrless n\,(y_f + y_b) + y_f.$$

It follows in this case, also, that y_f and y_b cannot have any common factor; and as their sum must be even, both of them may be odd, since U may be any number. They may, however, be equal to one another, and this is commonly the case.

General Formulæ for Drum Windings. In general, if y stands for the complete step from the first conductor of any group to the first conductor of the next group, m for the field step, and G for the total number of groups in the winding, we shall have, from the previous deductions:

$$mZ = mgG = \frac{1}{2} p\, y \pm c\,,$$

when

$$Z = \frac{p\, y \pm 2\, c}{2m}\ ;\ \text{and}\ y = \frac{2\, m\, Z \mp 2\, c}{p}\,,$$

which are the general formulæ for symmetrical windings, where g is the number of conductors per group.

For *lap windings* we have $m = 0$, so that,

$$y = \mp \frac{2\, c}{p}\,.$$

We may separate y into two parts y_f and y_b, of which either is negative, and either slightly less than or equal to $Z \div p$, and which differ from one another by $2c \div p$.

In *lap windings* the step of the winding at the commutator is related to the winding pitch by the simple rule:

$$y_k = y \div g.$$

Thus, in a simple winding of this type where $y = 2$, and where each element of the winding is a simple loop of two conductors so that $g = 2$, we would have $y_k = 1$.

For *wave windings*, $m = 1$, so that,

$$y = \frac{2Z \mp 2\, c}{p}\,;$$

and if this complete step is made up of equal front and back pitches, we shall have:

$$y_f = y_b = \frac{Z \mp c}{p}\,.$$

Re-entrancy of Windings. A winding which closes upon itself is called a *closed-coil winding*, as heretofore noted; also, because it re-enters upon itself, it is known as a *re-entrant winding*.

If the *whole* winding must be traversed before the first inductor is reached or re-entered, the winding is said to be *singly re-entrant*. If one-half the winding need be traversed before the inductor from which the start is made is again encountered, the winding is said to be *doubly re-entrant;* and so on for triply and other multiply re-entrant windings. The number of times the drum is passed *around* is of no consequence when considering the re-entrancy of a drum winding. For example, in Fig. 129, the drum is passed around 25 times before the conductor from which the start is made is reached, yet the winding is singly re-entrant, as shown by the winding table accompanying it.

Multiplex Windings. An armature may be wound with two or more independent windings, each of which may be singly re-entrant,

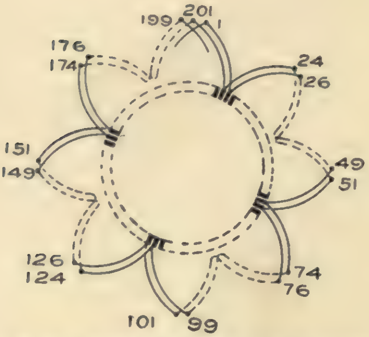


Fig. 129. Wave Winding, 8-Pole, 2-Circuit, Singly Re-entrant. (See Winding Table on Page 107.)

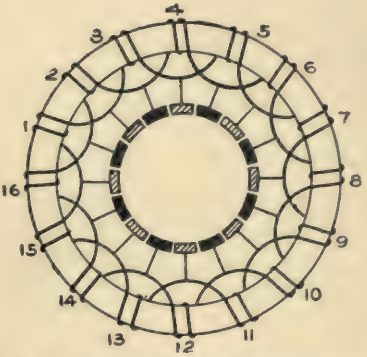


Fig. 130. Duplex Winding Consisting of Two Singly Re-entrant Ring Windings.

as shown in Fig. 130. These two windings might be furnished with two independent commutators situated at each end of the armature; but usually there is one with the number of its segments doubled, the two sets of bars being alternated between one another. In this case the brushes must be made broad enough to overlap at least two and one-half commutator bars, so as to collect current from both windings simultaneously. Such a winding is known as a *duplex singly re-entrant winding. Triplex-wound armatures* have three independent windings, with three sets of commutator bars similarly arranged.

The advantage of multiplex windings is that sparking at the brushes may be considerably lessened, for the coils are short-circuited a much shorter length of time and there is a longer brush-resistance path. Hence multiplex windings are much used in machines intended to supply large currents at small voltages, such as generators for electrolytic work.

WINDING TABLE FOR 8-POLE DRUM ARMATURE; 202 CONDUCTORS; TWO-CIRCUIT, SERIES-PARALLEL GROUPING; BRUSHES (±) 135° APART.

<table>
<tr><th>F</th><th colspan="2">B</th><th colspan="2">F</th><th colspan="2">B</th><th colspan="2">F</th><th colspan="2">B</th><th colspan="2">F</th><th colspan="2">B</th><th>F</th></tr>
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<tr><td colspan="2">197</td><td colspan="2">20</td><td colspan="2">45</td><td colspan="2">70</td><td colspan="2">95</td><td colspan="2">120</td><td colspan="2">145</td><td colspan="2">170</td></tr>
<tr><td colspan="2">195</td><td colspan="2">18</td><td colspan="2">43</td><td colspan="2">68</td><td colspan="2">93</td><td colspan="2">118</td><td colspan="2">143</td><td colspan="2">168</td></tr>
<tr><td colspan="2">193</td><td colspan="2">16</td><td colspan="2">41</td><td colspan="2">66</td><td colspan="2">91</td><td colspan="2">116</td><td colspan="2">141</td><td colspan="2">166</td></tr>
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<tr><td colspan="2">171</td><td colspan="2">196</td><td colspan="2">19</td><td colspan="2">44</td><td colspan="2">69</td><td colspan="2">94</td><td colspan="2">119</td><td colspan="2">144</td></tr>
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<tr><td colspan="2">161</td><td colspan="2">186</td><td colspan="2">9</td><td colspan="2">34</td><td colspan="2">59</td><td colspan="2">84</td><td colspan="2">109</td><td colspan="2">134</td></tr>
<tr><td colspan="2">159</td><td colspan="2">184</td><td colspan="2">7</td><td colspan="2">32</td><td colspan="2">57</td><td colspan="2">82</td><td colspan="2">107</td><td colspan="2">132</td></tr>
<tr><td colspan="2">157</td><td colspan="2">182</td><td colspan="2">5</td><td colspan="2">30</td><td colspan="2">55</td><td colspan="2">80</td><td colspan="2">105</td><td colspan="2">130</td></tr>
<tr><td colspan="2">155</td><td colspan="2">180</td><td colspan="2">3</td><td colspan="2">28</td><td colspan="2">53</td><td colspan="2">78</td><td colspan="2">103</td><td colspan="2">128</td></tr>
<tr><td colspan="2">153</td><td colspan="2">178</td><td colspan="2">1</td><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td></tr>
</table>

Paths in Parallel and Conductors in Series between Brushes. In a simplex lap winding there will be p paths in parallel between the brushes, and $Z \div p$ conductors in series. In a simplex wave winding, there will always be 2 paths in parallel through the armature, and each path will consist of $Z \div 2$ conductors in series.

A multipolar lap winding is often called a *parallel-grouped winding*, on account of the number of parallel paths through the armature. Sometimes it is called a *multiple-circuit winding* for the same reason. Similarly, a simplex wave winding is called either a *two-circuit winding* or a *series winding*.

Combining simplex windings to give a multiplex winding adds to the number of paths in parallel through the armature, but not the generated e. m. f. The latter is increased by multiplying the number of turns per coil, or the number of coils in series; but having a great number of turns per section (that is, element of the winding) aggravates the tendency to spark, as already shown (page 46).

Number of Brush Sets Required. Where there are p points around the commutator at which the voltage is zero (see page 35 for method of measuring potential around a commutator), p sets of brushes may be used in any case. In a lap winding, simplex or multiplex, p sets must be used in order to collect the full armature current; while in wave windings, simplex or multiplex, 2 sets of brushes are sufficient, though any number up to p may be used in order to insure sparkless collection of the armature current. For, by referring to Fig. 131, it is seen that if six brushes were placed around the commutator 60 degrees apart, the extra ones might be considered as cross-connections introduced to reduce the armature I^2R loss.

Conditions to be Satisfied by a Closed-Coil Drum Winding. A drum winding cannot have an odd number of inductors. Both the front and back pitches must be odd in simplex windings, for the odd-numbered conductors may be regarded as the returns for even-numbered ones.

Both the front and back pitches must be approximately equal to $Z \div p$, in order that conductors moving simultaneously under poles of opposite polarity should have their generated e. m. f.'s additive. The smallest pitch meeting this condition would stretch completely across a pole-face, while the largest would stretch from the given pole-tip to the next pole-tip of like polarity. When the front and back pitches differ considerably from $Z \div p$, the winding is called a *chord winding*, the name being due to the appearance of the end-connections. As we have seen, this method possesses the advantage of cutting down the demagnetizing effect of the armature; but it has the disadvantage that the two edges of any section are not both passing at the same time into a commutating field, so that it is not suitable for handling large outputs of current.

For a given number of inductors, the front and back pitches must be chosen so as to comply with the following conditions:

(*a*) All winding elements must be similar mechanically and electrically, and must be symmetrically placed upon the armature.

(*b*) In a simplex winding, every inductor must be passed over once only, and the winding must close upon itself, or be re-entrant.

(*c*) In a multiplex winding, each simplex element must comply with condition (*b*).

(*d*) A multiplex winding not consisting of complete and independent simplex windings (called a *singly re-entrant multiplex winding*), must as a whole satisfy condition (*b*).

(*e*) In a *two-layer winding* (that is, one where the conductors are placed one on top of another in a slot), it is usual to give the upper ones odd numbers, and the lower ones even numbers.

In addition to these conditions for drum windings in general, lap windings must also comply with the following:

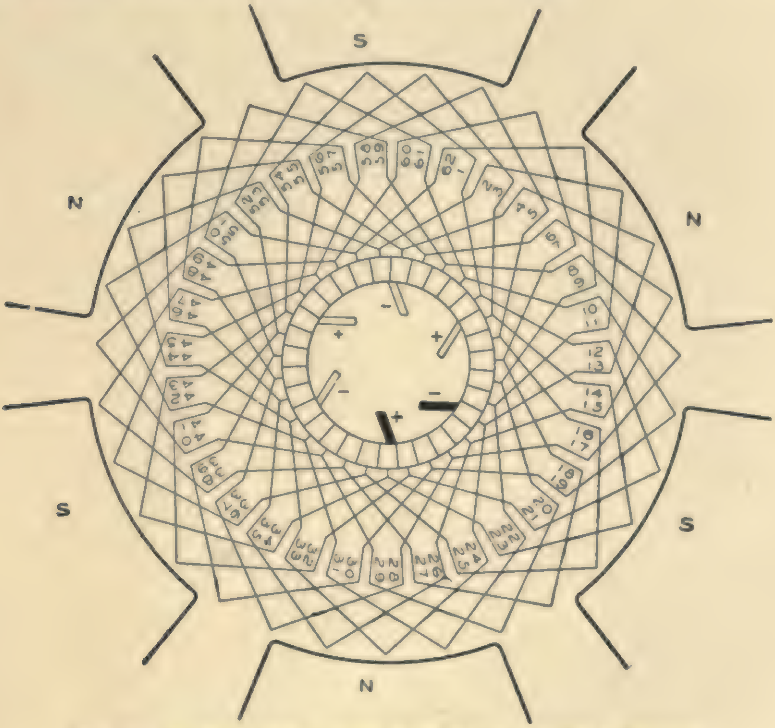


Fig. 131. Six-Pole Drum' Simplex Wave Winding, Singly Re-entrant.

(*a*) Front and back pitches must be opposite in sign.

(*b*) The front and back pitches must be unequal, otherwise the coil would be short-circuited upon itself.

(*c*) In a simplex lap winding, the front and back pitches differ by 2; that is $y_b = y_f \pm 2$.

(*d*) In a multiplex lap winding, the front and back pitches differ by $2x$, where x is the number of component simplex windings.

(*e*) Z may be any even number; and in slotted armatures, it must also be a multiple of the number of slots; the latter may be even or odd.

Wave windings must similarly comply with the following conditions:

(*a*) Front and back pitches must be alike in sign.

(*b*) Front and back pitches may be equal, or differ by any multiple of two. Usually they are both equal nearly to $Z \div p$, although one may be less, and the other greater.

(*c*) In simplex windings, $Z = p\,y_{av} \pm 2$.

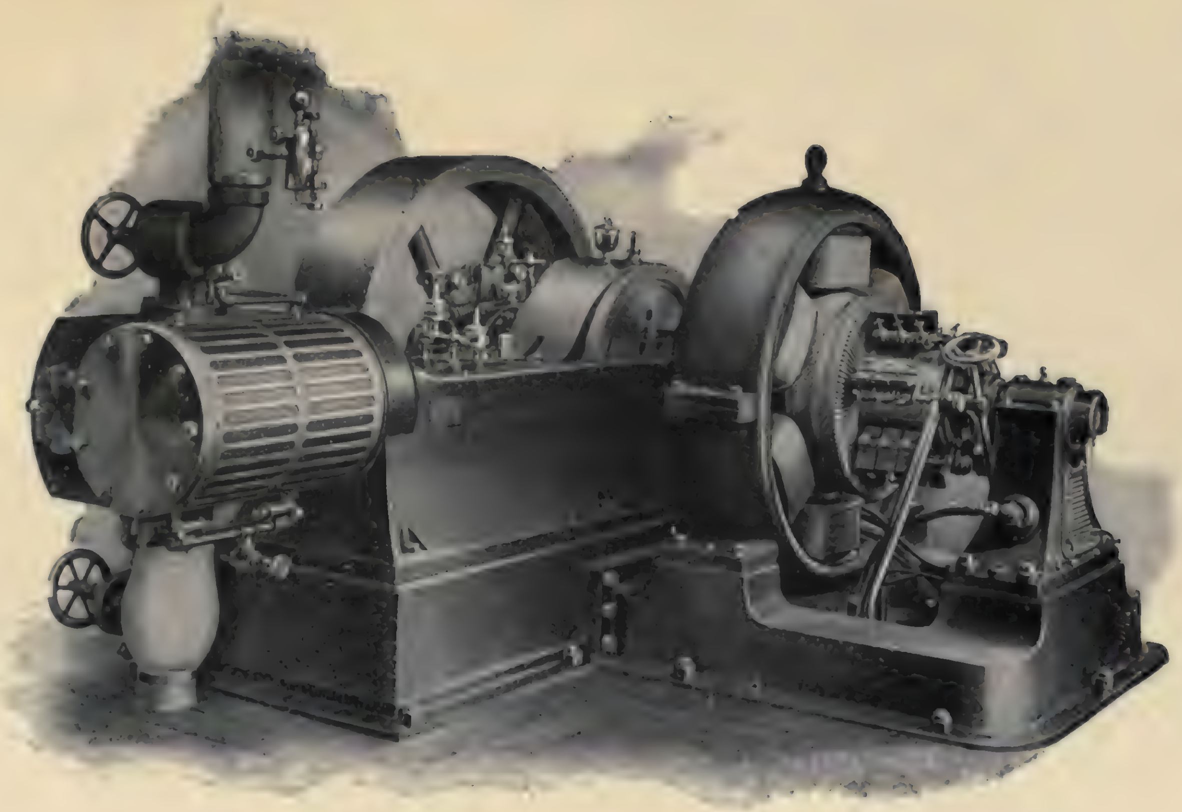
(*d*) In multiplex windings, $Z = p\,y_{av} \pm 2x$.

Resumé of Winding Formulæ. In Table VI will be found formulæ covering most of the types of ring and drum windings which are now used. The symbols in the columns have the same significance as those used in the text.

Equipotential Connections. As the armature in practice is not always centered exactly with respect to the pole-pieces—and, further, since the conductors are not equidistant from the latter, because of winding inequalities—the generated e. m. f. of the various sections will not be exactly equal. Hence there will be cross-currents internal to the armature, which increase sparking at the commutator and heating of the armature. In wave windings, the conductors are connected in series and so distributed as to have no perceptible tendency to produce cross-currents; but in lap windings, inaccurate centering may lead to the production of large local currents. In order to reduce their production as much as possible, it is customary, in large generators or in others liable to be so affected, to connect through low-resistance leads, the bars, or conductors at the same voltage. These connections are called *equipotential connections;* and although they reduce the sparking tendency due to local currents in the armature, they add a little to the heating of the armature.

Examples of Armature Windings. On the following pages will be found examples of windings in common use. In Figs. 131 to 137 inclusive, the short, radial, numbered lines represent the conductors; the crossed lines outside of the circle of conductors represent the connections at the back end of the armature; and the crossed lines between the circle of conductors and the commutator at the center, represent the connections at the front end of the armature. For the sake of simplicity, only a few conductors are shown in these examples; and it should be noted that in actual designs, their number Z attains a much greater value.

Fig. 132 represents a six-pole drum simplex singly re-entrant lap winding, with 60 conductors, a front pitch of −11, and a back pitch of + 9. In this particular case the general progression of the



HORIZONTAL ENGINE DIRECT-CONNECTED TO GENERATOR.

New York Safety Steam Power Company.

winding is around the drum in an anti-clockwise direction, and on this account it is sometimes called a *retrogressive* winding to distinguish it from a clockwise one, which is called a *progressive* winding. The winding here shown has a commutator pitch of −1, and there are six paths in parallel through the armature, necessitating six brush sets unless the winding or commutator is cross-connected (see Fig. 125).

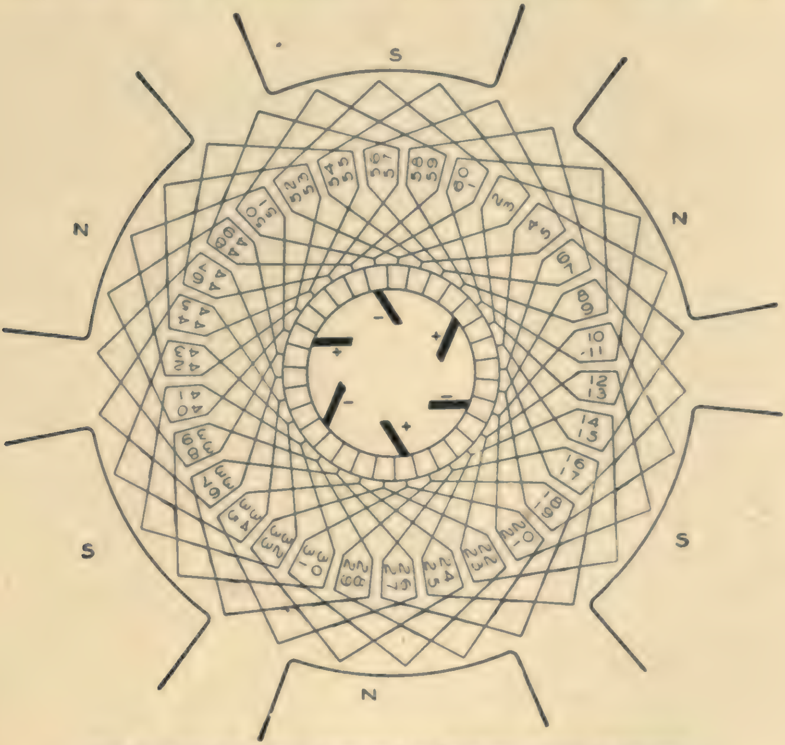


Fig. 132. Six-Pole Drum Simplex Lap Winding, Singly Re-entrant.

Fig. 131 illustrates a six-pole drum simplex singly re-entrant wave winding of 62 inductors. It has a front pitch of +11, and a back pitch of +9, giving an average pitch of 10, and a commutator pitch of 10 also. This winding has two paths in parallel through the armature, so that only two brush sets are required. The locations of the other brush sets, which may be added if large currents are to be collected, are also indicated by dotted lines.

Fig. 133 shows a six-pole drum duplex doubly re-entrant lap winding composed of 60 inductors with a front pitch of −11, a back

TABLE VI

Formulæ for Ring and Drum Windings

RING WINDINGS

Types of Winding	No. Circuits in Parallel through Arm. $= c$	No. Circuits in Parallel per Winding $= c_1$	No. Separate Windings $= x$	Field Step $= m$	No. Conductors $= Z$	Resultant Pitch $= y$	Commutator Pitch $= y_k$	Conductors in Series between Brushes	No. Brush Sets	Angle between Brush Sets	Figs. Illustrating Winding
A*	ϕ	ϕ	1	0	$= g\,G = g\,K$	$\pm g$	$\pm g$	$Z \div p$	p	$360° \div p$	....
B	2	2	1	1	$= \frac{g\,p\,y \pm 2}{2}$ and $= g\,G = g\,K$	$\frac{2\,Z \mp 2}{p}$ and must be odd	$\frac{2\,K \mp 2}{p}$	$Z \div 2$	Min. 2 Max. p	$360° \div p$ or any odd multiple	....
C	4, 6, 8, or any other even number > 2	c	1	1	$\frac{p\,y \pm c}{2}$	$\frac{2\,Z \mp c}{2}$	$\frac{2\,K \mp c}{p}$	$Z \div c$	p	$360° \div p$	....
D	$x\,p$	p	2, 3, 4, or any other whole number	0	$= x\,g\,b = x\,g\,k$	$\pm\, g\,x$	$\pm\, g\,x$	$Z \div x\,p$	p	$360° \div p$	....
E	$2\,x$	2	do	1	$\frac{g\,n\,p\,y \pm 2\,n}{2}$	$\frac{2\,Z \mp 2\,x}{x\,p}$	$\frac{2\,K \mp 2\,x}{p}$	$Z \div 2\,x$	Max. p Min. 2	$360° \div p$ or any odd multiple	....
F	$x\,c_1$	4, 6, 8, or any other even number > 2	do	1	$\frac{g\,n\,p\,y \pm 2\,n\,c_1}{2}$	$\frac{2\,Z \mp 2\,x\,c_1}{x\,p}$	$\frac{2\,K \mp 2\,x\,c_1}{x\,p}$	$Z \div x\,c_1$	p	$360° \div p$	....

LAP-WOUND DRUM WINDINGS

Types of Winding	No. Circuits in Parallel through Arm. $= c$	No. Conductors in Series between Brushes	No. Separate Windings $= x$	No. Circuits in Parallel per Winding $= c_1$	Field Step $= m$	No. Armature Conductors $= Z$	Resultant Pitch $= y$	Forward Pitch $= y_f$	Backward Pitch $= y_b$	Commutator Pitch $= y_k$	No. Brush Sets	Angle between Brush Sets	Figs. Illustrating Winding
G*	p	$Z \div p$	1	p	0	$Z = 2\,g\,G = 2\,g\,Z$, *i. e.*, any even number	$\pm\, 2$	Equal to or less than $\frac{Z}{p}$, and must be odd	$-(y_f \pm 2)$	1	p	$360° \div p$	132
H	$p\,x$	$Z \div p\,x$	2, 3, 4, or any other whole number	p	0		$\pm\, 2\,x$		$y_f - 2\,x$	$\pm\, x$	p	$360° \div p$	....
J	4, 6, 8, or any other even number > 2	$Z \div c$	1	4, 6, 8, or any other even number > 2	0		$\pm\, c$		$y_f - c$	$\pm\, \frac{1}{2}\,c$	ϕ	$360° \div p$	135
K	$x\,c_1$	$Z \div x\,c_1$	2, 3, 4, or any other whole number	do x p	0		$\pm\, x\,c_1$		$y_f - x\,c_1$	$\pm\, \frac{1}{2}\,x\,c_1$	p	$360° \div p$	133

WAVE-WOUND DRUM WINDINGS

Types of Winding	No. Circuits in Parallel through Arm. = c	No. Conductors in Series between Brushes	No. Separate Windings = x	No. Circuits in Parallel per Winding = c_1	Field Step = m	No. Conductors = Z	$y_f = y_b$	Commutator Pitch = y_k	No. Brush Sets	Angle between Brush Sets	Figs. Illustrating Winding
L*[*]	2	$Z+2$	1	2	1	$p\,y_{av} \mp 2$	$\frac{Z \mp 2}{p}$ must be odd and have no common factor with Z	$\frac{2K \mp 2}{p}$	Min. 2 Max. p	360° + p. or any odd multiple	133
M	$x\,c_1$	$Z+x\,c_1$	2, 3, 4, or any other whole number	2	1	$x\,p\,y_{av} \pm 2x$	$\frac{Z \mp 2x}{x\,p}$ where y_{av} is even y_f may $= y_{av}+1$ y_b may $= y_{av}-1$	$\frac{2K \mp 2x}{x\,p}$	Min. 2 Max. p		137
N	4, 6, or any other even number > 2	$Z+c$	1	4, 6, 8, or any other even number > 2	1	$p\,y_{av} \mp c$	$\frac{Z \mp c}{p}$	$\frac{2K \mp c}{p}$	Min. 2 Max. p		136
P	$x\,c_1$	$Z+x\,c_1$	2, 3, 4, or any other whole number	2, 4, 6, or any other even number	1	$x\,p\,y_{av} \pm x\,c_1$	$\frac{Z \mp x\,c_1}{x\,p}$	$\frac{2K \mp x\,c_1}{x\,p}$	Min. 2 Max. p		134

[*] Key to Special Types of Ring, Lap, and Wave Windings is given below:

KEY TO TABLE VI

Following is a key to the special types of Ring, Lap, and Wave Windings for which formulæ are given in Table VI:

RING WINDINGS

A—Parallel Grouping (Simplex).
B—Series Grouping (Singly Re-entrant).
C—Series-Parallel Grouping (Simplex Doubly or Multiply Re-entrant).

D—Duplex or Multiplex Parallel Grouping.
E—Duplex or Multiplex Series Grouping.
F—Duplex or Multiplex Series-Parallel Grouping.

LAP-WOUND DRUM WINDINGS

G—Simplex Singly Re-entrant (Parallel) Lap Winding.
H—Duplex or Multiplex (Parallel) Lap Winding.
J—Simplex (Series-Parallel) Doubly or Multiply Re-entrant Lap Winding.
K—Duplex or Multiplex (Series-Parallel) Doubly or Multiply Re-entrant Lap Winding.

WAVE-WOUND DRUM WINDINGS

L—Simplex Singly Re-entrant (Series) Wave Winding.
M—Duplex or Multiplex (Series) Wave Winding.
N—Simplex Doubly or Multiply Re-entrant (Series-Parallel) Wave Winding.
P—Duplex or Multiplex Doubly or Multiply Re-entrant (Series-Parallel) Wave Winding.

pitch of +7, a commutator pitch of −2, and 12 paths in parallel through the armature. This winding is also retrogressive, and composed of two complete but distinct simplex singly re-entrant lap windings, each having 30 inductors. One set is represented by the full lines, the other by the broken lines, their respective commutator segments being unshaded and shaded. It should be noted that with

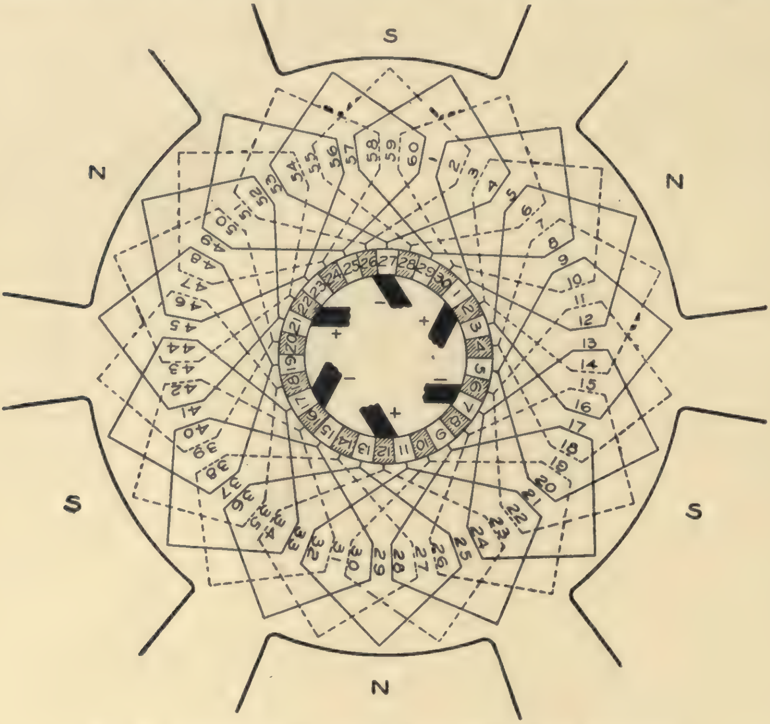


Fig. 133. Six-Pole Drum Duplex Lap Winding, Doubly Re-entrant.

a duplex or any other multiplex winding, the brushes must be wide enough to cover at least as many segments as there are windings. Here the brushes cover two segments.

Fig. 134 represents a six-pole drum duplex doubly re-entrant wave winding, consisting of 64 inductors, having a front pitch of +9, a back pitch of +11, and a commutator pitch of 10. The average pitch is 10, and there are four paths in parallel through the armature. Nevertheless only two brushes are required to collect the current, although others may be added as indicated, if desired. It consists of two complete simplex singly re-entrant wave windings; hence its appellation, *duplex doubly re-entrant.*

Fig. 135 represents a four-pole drum simplex doubly re-entrant lap winding having 34 inductors. In this case the front pitch is +9, the back pitch is −5, and the commutator pitch is +2, while there are 8 paths in parallel through the armature. Four brushes only are required, and inspection shows this to be a progressive winding.

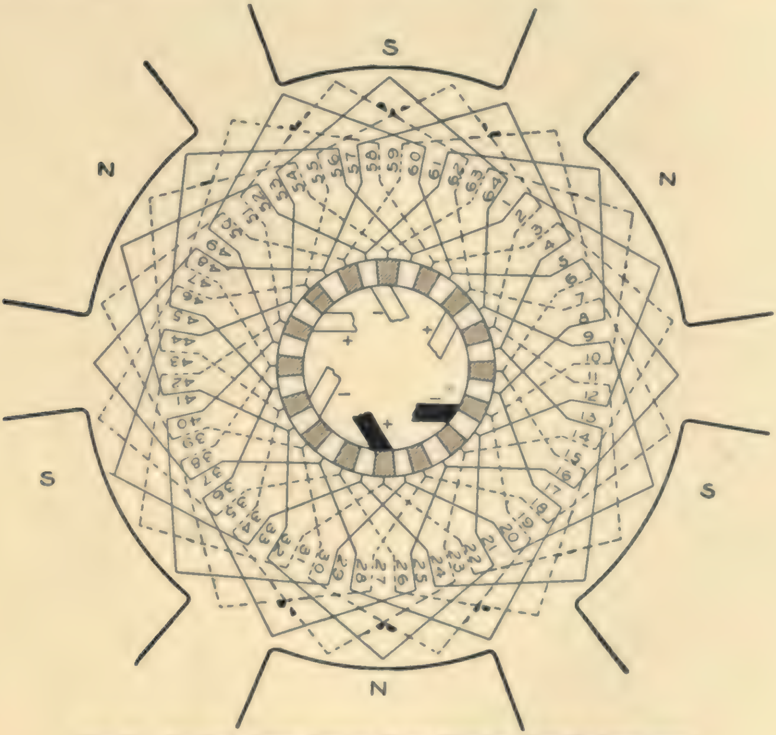


Fig. 134. Six-Pole Drum Duplex Wave Winding, Doubly Re-entrant.

Fig. 136 illustrates a four-pole drum simplex trebly re-entrant wave winding having 34 inductors, with a front pitch of −11 and a back pitch of −9. The commutator pitch is −10, and it is seen that this is a retrogressive winding, having six circuits in parallel through the armature.

In Fig. 137 we have a six-pole drum duplex singly re-entrant wave winding, with a back pitch of 11, a front pitch of 9, an average pitch and a commutator pitch of 10. It has two paths in parallel through the armature; and although only two brushes are required, six sets may be used if desired, as indicated. It is a progressive winding.

Length of Armature Winding. The length of wire in an armature winding depends upon the particular type of winding employed. Determination of this length is necessary in the design of dynamo-electric machinery in order to compute the armature resistance and the resulting regulation of the machine. G. Simonds,* J. Dalemont,** H. M. Hobart,† and A. I. M. Winetraub†† have given methods for computing the lengths of winding necessitated by the different types; but the method usually employed by manufac-

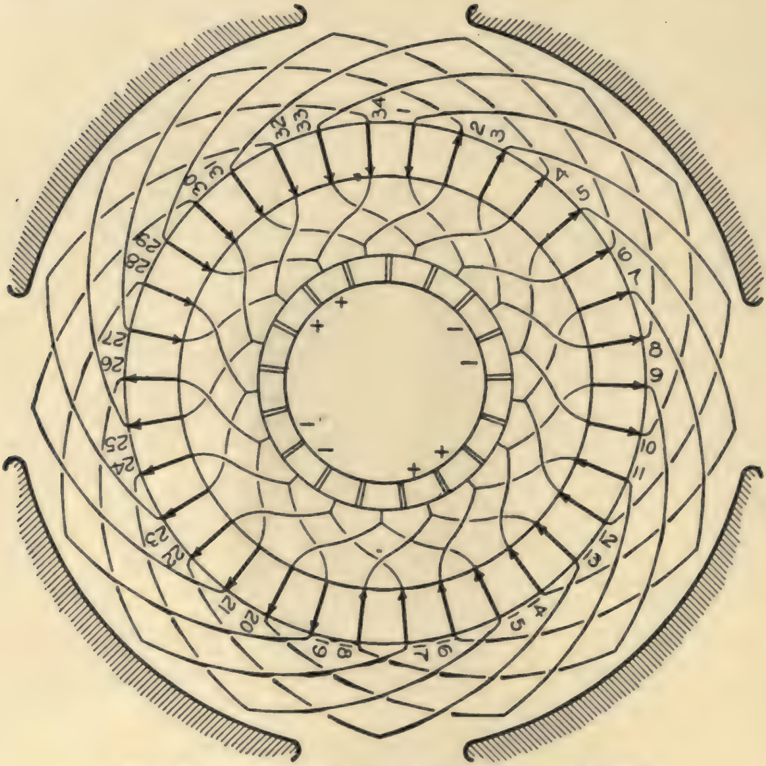


Fig. 135. Drum Simplex Doubly Re-entrant Lap Winding.

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* *Electrical World*, March 3, 1900.

** Bulletin of the Institute Montefiore, 11, 428, 1902.

† *Traction and Transmission*, V, 239, 1903.

†† *Electrical World*, August 25, 1906.

turers consists simply in drawing the armature to scale, and laying off thereon a section of the winding, the requisite length of wire being then determined by actual measurement. In particularly important cases—for example, when a new type of machine is to be built in large numbers or sizes—a portion of a dummy armature core is made of wood and wound with the correct size of wire. The length thus employed for one section is then multiplied by the number of sections to obtain the total length of wire required.

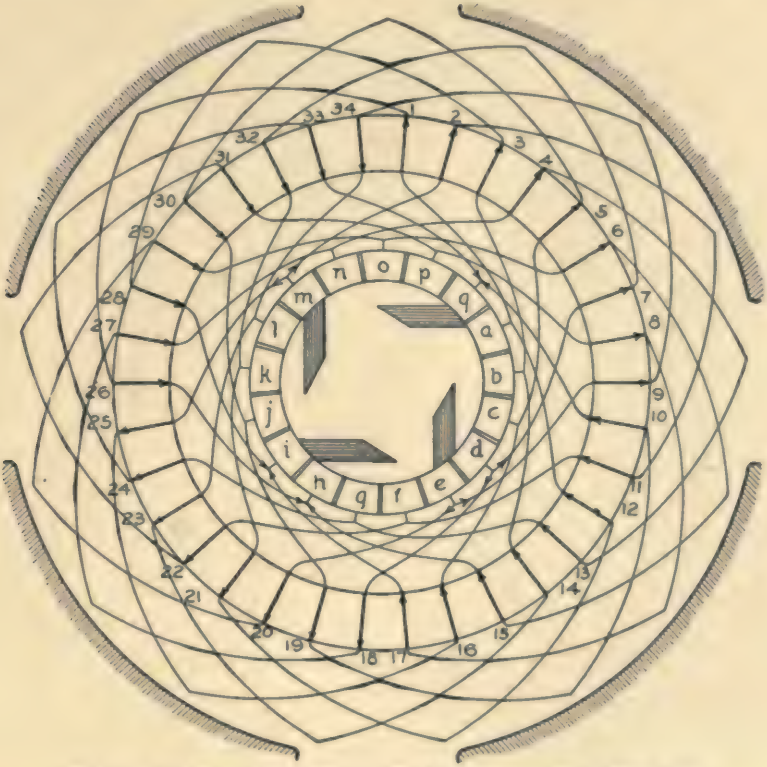

Fig. 136. Six-Circuit Drum Simplex Trebly Re-entrant Wave Winding.

Armature Resistance. Having obtained the length of wire required for the winding, the resistance of the armature may be calculated from the formula,

$$r_a = \frac{\rho\, l}{c^2 s},$$

wherein ρ is the resistance of a unit-length of copper of unit cross-section; l is the total length of the armature winding in the same linear units as ρ; c represents the number of circuits in parallel through the armature; and s is the cross-sectional area of the conductor in the same units as that upon which the value of ρ is based.

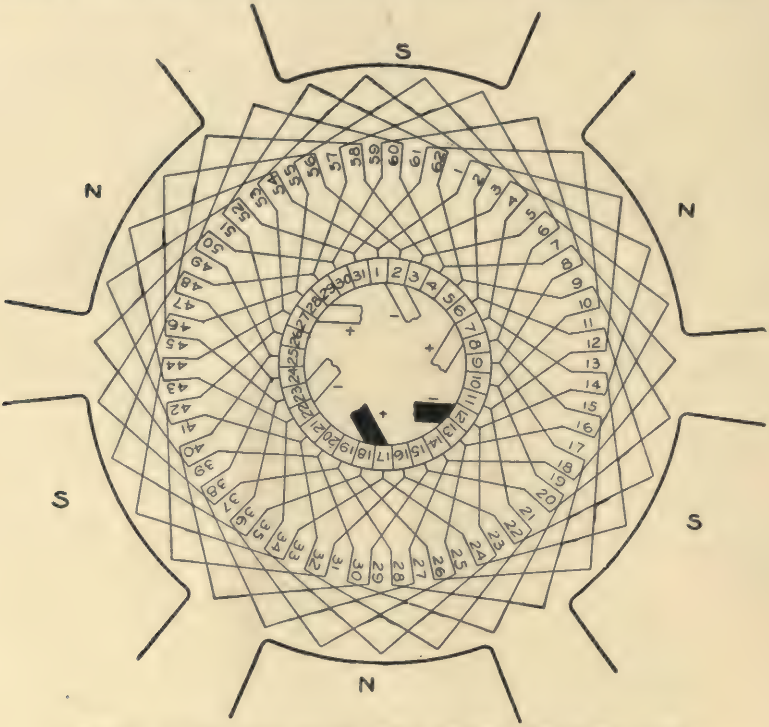

Fig. 137. Six-Pole Drum Duplex Wave Winding, Singly Re-entrant.

A circular conductor one foot long and one mil (0.001 inch) in diameter is called a *circular mil foot;* and if composed of standard copper, it has at 20° Centigrade a resistance of 10.35 ohms, and at 0° Centigrade a resistance of 9.55 ohms. At any other temperature t, the resistance R_t is:

$$R_t = 9.55\,(1 + 0.0042t).$$

If we take as our basis of calculation a square conductor, the cross-section being a square each of whose sides is one mil long, we have a *square mil foot,* which has an area $4 \div \pi$ times that of a circular mil foot. Hence its resistance is $\pi \div 4$, or 0.7854 of that of a circular mil foot. Hence the resistance of a square mil foot of copper wire at 20° C. is $10.35 \times 0.7854 = 8.15$ ohms, and at 0° C. it is $9.55 \times 0.7854 = 7.5$ ohms.

The resistance of any copper conductor, the cross-section of which is given in circular mils, is at 20° C. equal to $\frac{10.35 \times l}{d^2}$, where l is the length of the conductor in feet, and d^2 is the cross-section in circular mils (that is, the square of the diameter in mils).

Example. 1,200 feet of copper wire 0.1 inch (100 mils) in diameter is required for a certain six-circuit armature winding. Substituting in the equation $r_a = \frac{\rho\, l}{c^2\, s}$, we have for the resistance of the armature:

$$r_a = \frac{10.35 \times 1,200}{36 \times 10,000} = 0.0345 \text{ ohm at } 20°\text{C.}$$

Armature Losses. The losses in the armature may be divided into those due to the resistance of its winding, and those due to the hysteresis and eddy currents in its iron core.*

Under the preceding heading, a method of finding the resistance of the armature winding was given; hence the copper loss in the armature due to the resistance of its winding is:

$$w_{cu} = I_a^2\, r_a.$$

For calculating the hysteresis loss w_h in the armature, we may use the formula and curves given on page 14, or may refer to a curve obtained by test upon the iron to be used. Similarly, the eddy-current loss w_e may be computed from the formula given on page 15, or from the graphs of Fig. 17. The total iron loss in the armature is therefore:

$$w_i = w_e + w_h.$$

It is found, however, by tests upon actual machines, that the iron losses thus computed are considerably lower than the true values. This is no doubt due to unequal distribution of flux in the various parts of the magnetic circuit subject to a varying flux-density; also to the departure from the ideal conditions in the matter of dispersion, and to the presence of wasteful currents in other parts of the machine. Prof. J. Epstein† gives curves, Fig. 138, showing that the calculated losses of a machine based on any of the heretofore standard data would be low; hence the actual commercial efficiency is lower than the computed.

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* Windage due to the rotation of the armature will be dealt with under a later heading.

† Proceedings of the Institution of Electrical Engineers of Great Britain, Nov. 11, 1906.

In addition to the calculated iron and copper losses, there may be a loss in the armature conductors due to eddy currents, and another loss if for any reason the current does not distribute itself evenly through the conductor. Also, if the division of current between the parallel circuits of the armature winding is not uniform, and equalizing connections are not provided, an additional loss results. These are so obscure as to baffle computation; and as their value is small, they may be neglected.

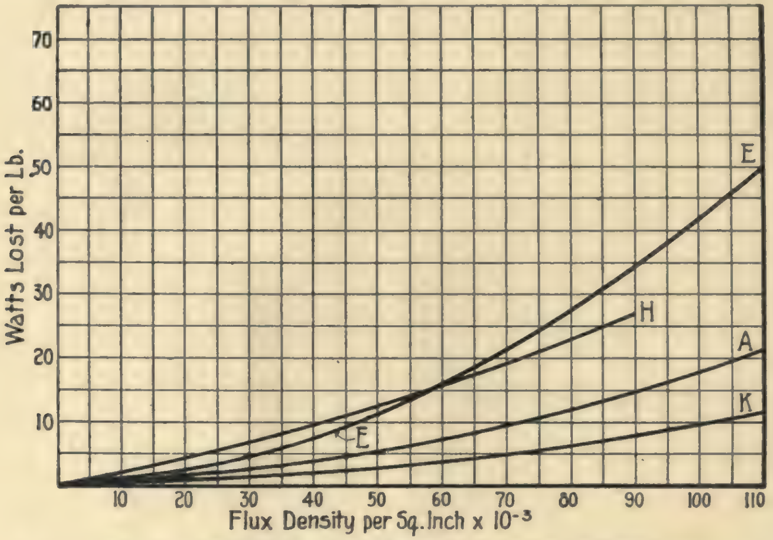

Fig. 138. Standard Iron-Loss Curves at 30 Cycles per Second. *E*—Prof. Epstein; *H*—Hobart, "Electric Motors;" *A*—Prof. Arnold, *Die Gleichstrommaschine*; *K*—G. Kapp, *Gleichstrom und Wechselstrom.*

Heating of Armatures. The amount of heat which will be dissipated by a unit-surface of a moving armature depends upon:

(1) Resistance, eddy-current, and hysteresis losses in the armature.

(2) Heat-radiating surface of the armature.

(3) Peripheral speed of the armature.

(4) Proportion, within limits, of the ratio of the radiating surface to polar surface.

(5) Temperature of the radiating surface.

The first of these is dependent upon the internal actions of the armature, and represents the total heat which must be dissipated.

The surface exposed to the cooling action of the air is somewhat indefinite, but in most cases the total peripheral surface of the armature is assumed as radiating surface, and to this may be added one-half the surface of the ends of the armature.

As the peripheral speed of the armature becomes greater, it is found that the radiating capability of its surface increases, though not in direct proportion.

Messrs. A. H. and C. E. Timmerman* found by actual test that the effect of pole-faces above a surface is to interfere with the radiation of heat. As the proportion of surface covered by the pole-faces became larger, the amount of heat radiated per degree rise in temperature became less. They also found that elevation in temperature of a surface caused an increase in the radiation of heat per degree rise in temperature, but that this rate diminished as the temperature rose.

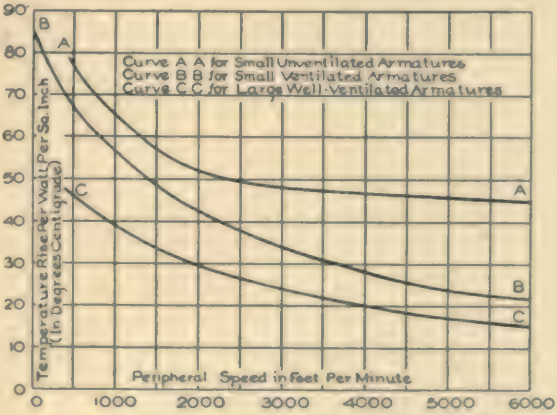

Fig. 139. Curves for Estimating Temperature-Rise.

Various formulæ may be given for estimating the ultimate rise in temperature of armatures; but as most of them are empirical and clumsy, the curves of Fig. 139 have been substituted. With their aid, we may determine the temperature-rise in degrees Centigrade of an armature at any usual peripheral speed, if we know the total radiating surface and the total armature losses.

Example. In a 480-kilowatt generator, the heat-radiating surface of the armature was computed to be about 5,000 square inches, while total losses in the armature were found to be 12,330 watts by calculation. Hence the watts wasted per square inch of heat-radiating surface are 12,330 ÷ 5,000 = 2.46.

As the peripheral speed of the armature in this instance was 4,500 feet per minute, we see by reference to the curves of Fig. 139, that there will be a rise of 19° C. for each watt per square inch. Hence the temperature-rise of this armature will be approximately:

$$\theta_a = 2.46 \times 19 = 47° \text{ C.}$$

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* Transactions of the American Institute of Electrical Engineers, Vol. X. 1893.

Commutator and Brush Calculations. Commutators for continuous-current machines may be divided into two classes, depending upon whether they are for *open* or *closed-coil* armature windings. In the former special case, used for arc-lighting generators, the commutator has a small number of segments separated from each other by an air-gap, and each covering a considerable angle. With closed-coil windings, ordinarily used for direct-current lighting and power, in which case the terminal voltage is kept comparatively constant (in contradistinction to series arc-lighting machines, for which the current is constant), the commutator is of the original Pacinotti type —that is, consisting of a considerable number of parallel bars or segments separated by strips of insulation, usually mica. In both cases the completed commutator presents a cylindrical surface against which the brushes press.

Number of Segments. The number of segments depends upon the number of sections of the winding, as shown on page 95. We have also seen (page 49) that increasing the number of commutator segments reduces the tendency to spark at the brushes. This increase is limited, however, by the matter of cost, and the fact that the number of sections in a drum-wound armature can never exceed one-half the number of inductors, while, in a ring-wound armature, the number of sections can never be greater than the number of inductors.

The proper number of segments is therefore determined by the winding of the armature, which depends upon the voltage and output of the machine. If by experience the suitable number of average volts per segment e_k of the commutator be known, then K, the number of segments, may be readily computed from the following formula:

$$K = E c \div e_k.$$

Experience shows that the values of e_k indicated in Table VII, may be chosen, although the matter is influenced by the current to be collected. If the latter be less than 100 amperes, then the value of e_k may be increased, but in no case should it exceed 25 volts.

Arnold has given the rule that the number of commutator segments must *never be less than* from 0.037 to 0.04 times the product of the number of armature inductors into the square root of the current carried by one circuit of the armature. This rule is an empirical one based on observations with regard to sparking; nevertheless it has been found that good machines were built in which the constant was slightly less than 0.037.

Example. A 1,000-kilowatt generator having 16 paths in parallel through its armature produced 500 volts at its terminals. The number of armature conductors was 2,304. Hence, according to Arnold's rule, K must not be less than $0.037 \times 2{,}304 \sqrt{2{,}000 \div 12} = 956$. As a matter of fact, 1,152 segments were taken for this machine, making the number of segments equal to one-half the number of conductors.

TABLE VII

Voltage and Number of Segments

For Machines Working at	Average Volts per Segment=e_k	Average Segments per Pole or Circuit
500 to 650 volts	5 to 12	40 to 150 or more
200 to 250 volts	3 to 8	25 to 75
100 to 130 volts	2 to 4	20 to 50

Size of the Commutator. The size of the commutator depends upon the number of segments, their thickness and that of the insulation between them, and the length of the segments parallel to the shaft. The diameter is limited by the peripheral speed allowable. The length depends upon the amount of current to be collected, a density of 50 amperes per square inch being as much as should be allowed for the contact area between a carbon brush and the bar. Bars are rarely ever thinner than 0.2 in., or with insulation say 0.3 in., and the peripheral speed of a commutator seldom exceeds 2,500 feet per minute; so that by keeping within these limits good results may be expected. A favorite size for commutator diam-

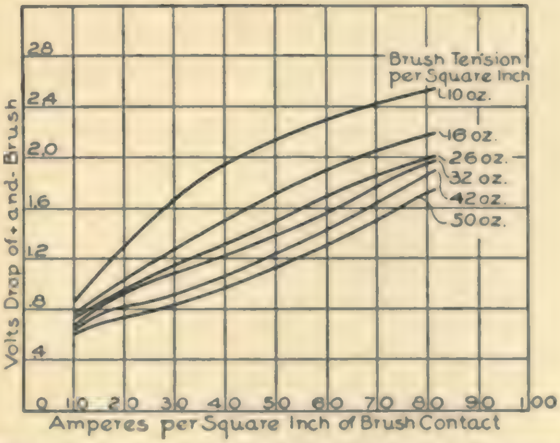


Fig. 140. Curves Showing Average Brush Drop with Various Brush Tensions and Current-Densities.

eters is $\frac{3}{4}$ that of the armature diameter, which serves as another guide.

Commutator Losses. The losses which the commutator surface must take care of may be divided into those arising from the resistance, or more properly the voltage drop, of the brush contact, and from the friction of the brushes against the rotating commutator. The former depends mainly upon the following factors:

(1) Material of the brushes.

(2) Pressure of the brushes upon the commutator.

(3) Peripheral speed of the commutator.

(4) Current-density in the brush.

(5) Condition of the commutator and brushes.

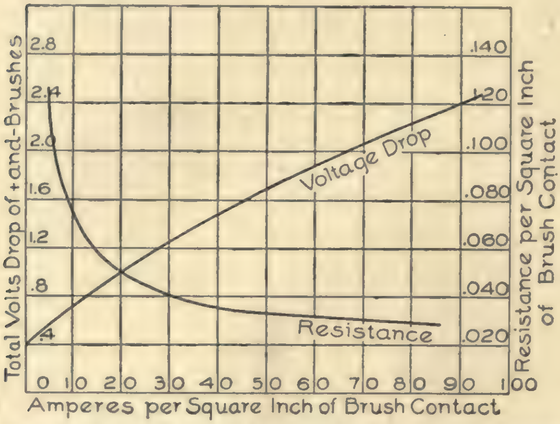


Fig. 141. Curves Showing Average Brush Drop and Contact Resistance at Various Current-Densities for Several Standard Grades of Carbon and Graphite Brushes.

The loss due to friction of the brushes upon the commutator varies with:

(1) Pressure of the brushes.

(2) Peripheral speed of the commutator.

(3) Coefficient of friction between commutator and brushes.

Fig. 141 shows the effect of various current-densities with various grades of brushes; and this may be taken as illustrating the influence of the material of the brush upon its contact resistance. Fig. 140 shows how the pressure of the brushes affects the voltage-drop; while Fig. 142 indicates the effect of peripheral speed of the commutator upon this drop, if we divide the watts loss by the amperes per square inch of brush contact; and Fig. 141 illustrates the relation between the current density in the brush and the voltage-drop across both positive and negative brushes. The influence of the condition of the commutator and brushes upon contact resistance cannot be stated exactly; but it is a fact that if either be in bad condition, the losses at the commutator may be increased many fold.

Multiplying the volts drop obtained from Fig. 141, by the current per brush set, we obtain the energy loss due to brush-contact resistance. For example, if we design the brushes so that the current-density in them is 35 amperes per square inch at rated load, we have a drop over the contact surfaces of both positive and negative brushes of 1.35 volts; and multiplying the total current output by 1.35 gives the watts lost.

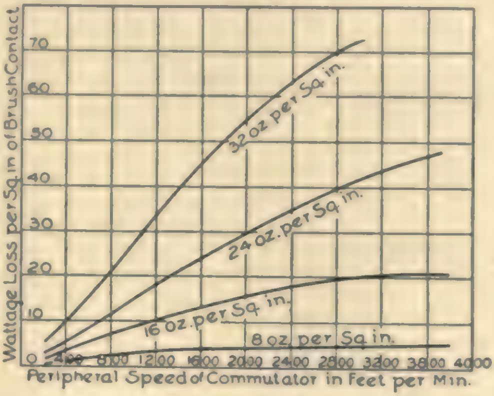


Fig. 142. Curves Showing Average Friction Loss per Square Inch of Brush Contact at Various Speeds and Brush Tensions.

Example. In a 100-kilowatt machine of one of the large manufacturing companies, the current collected by the brushes amounted to 415 amperes. If the current-density in the brushes had been 35 amperes per square inch, the loss due to contact resistance would have been:

$$1.35 \times 415 = 560 \text{ watts.}$$

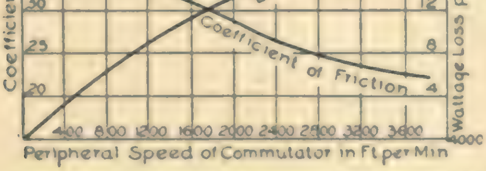


Fig. 143. Curves Showing Average Coefficient of Friction and Brush-Friction Loss for Different Grades of Brushes at Various Commutator Speeds, with Brush Tension of 1 lb. per Square Inch.

The variation of friction losses (which the surface of the commutator must radiate as heat) with peripheral speed of the commutator at various pressures, is shown graphically in Fig. 142; while the dependence of the coefficient of friction upon the commutator peripheral speed is indicated by Fig. 143 for carbon brushes in good condition.

To compute the watts lost through brush friction, multiply the total area of brush contact by the stress—*i.e.*, the pressure per unit area—to get the total pressure in pounds. Then multiply this value by the coefficient of friction and peripheral speed in feet per minute of the commutator, which gives the losses in foot-pounds per minute. Dividing by 33,000 to convert this value into horse-power, and multiplying by 746, we convert the result thus obtained into watts.

Example. Taking the same machine as just above mentioned, let us assume the brush pressure as 1.5 pounds per square inch, the total brush area as 23.7 sq. in., the peripheral speed of the commutator as 2,500 feet per minute, and the coefficient of friction as 0.27. We have the friction loss:

$$23.7 \times 1.5 \times 0.27 \times 2{,}500 \times 746 \div 33{,}000 = 543 \text{ watts (nearly).}$$

Commutator Heating. The final temperature which the commutator surface will attain depends upon the total losses to be radiated by it and the radiating surface, together with the peripheral speed. According to tests made by Prof. E. Arnold, the final rise in temperature of the commutator in degrees Centigrade will be:

$$\theta = \frac{46.5 \times w_c}{A_c\,(1 + 0.005\,v)},$$

in which w_c represents the total commutator losses, electrical and mechanical, in watts; A_c represents the radiating surface of the commutator in square inches; and v represents the peripheral speed of the commutator in feet per minute.

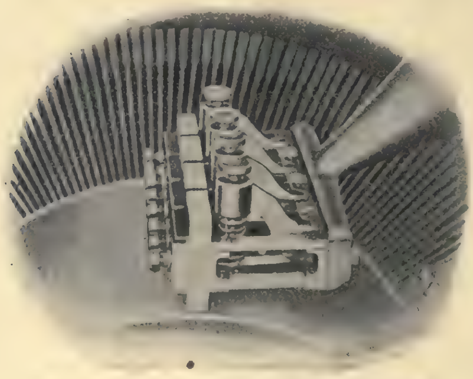
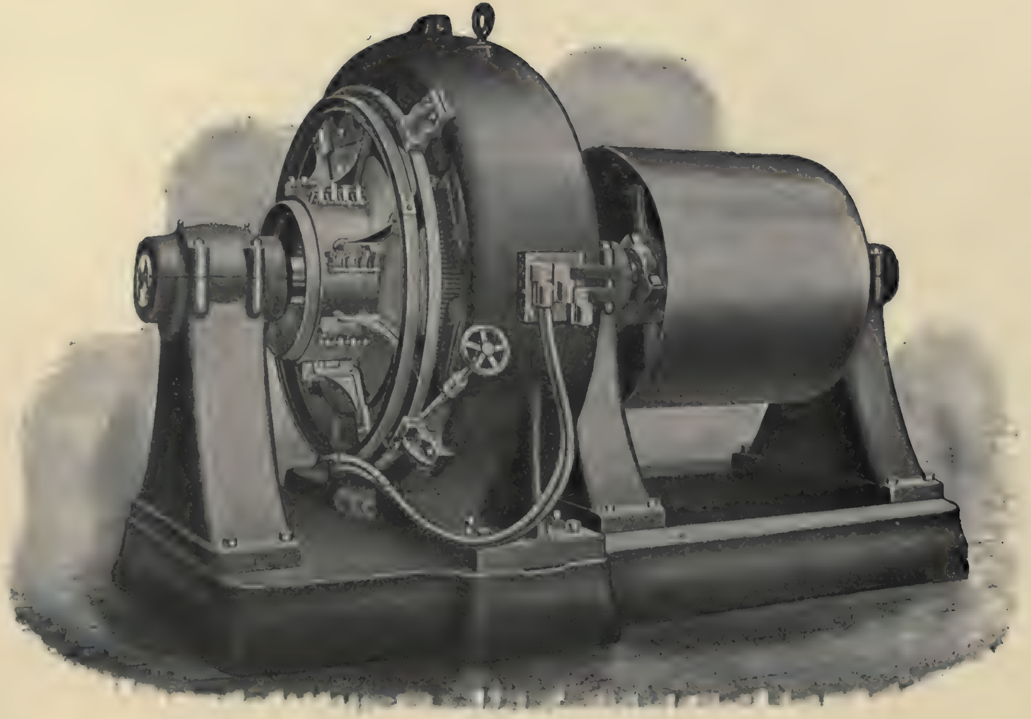


Fig. 144. Parallel-Movement Brush-Holder. Crocker-Wheeler Company.

According to Messrs. Parshall and Hobart, the rise in temperature of the commutator will seldom exceed 20° C. with one watt per square inch of peripheral radiating surface at a peripheral speed of 2,500 ft. per minute, a figure which may be much improved upon with ventilated armatures.

Number and Size of Brushes. The total number of brush sets is usually fixed by the type of armature winding, as previously stated; but this criterion gives us no clew to the number of brushes per set. In all but the smallest machines, it is usual to place at least two brushes exactly similar, side by side (Fig. 144 shows four), instead of one broad brush, thus allowing one brush to be removed for trimming or



350 K.W. 350 R.P.M. THREE-BEARING BELTED GENERATOR.

Triumph Electric Company.

renewal while the machine is running. The contact between the brushes and the commutator is made much better by this subdivision, for a slight inequality at one point of the latter may slightly raise one brush of a set at each revolution, without much harm, while, with one broad brush, the entire brush would be lifted, causing bad sparking. Subdivision of the brush also tends to equalize the wear upon the commutator, each brush being separately held against the commutator, and the gap between two adjacent brushes of the same set being bridged by the brushes of the other set or sets. The number of individual brushes in each group depends upon the current capacity and size of machine and the judgment of the designer, and varies from two to eight or more.

The proper thickness for carbon brushes cannot be stated definitely, but they are usually made to span 2½ bars in armatures having simplex windings. For armatures with duplex and triplex windings, thicker brushes must necessarily be used. The usual thickness of metal brushes spans about 1½ commutator bars.

Table VIII gives standard sizes of carbon brushes employed by most manufacturing companies; and in designing a generator or motor it is best to select one of these sizes that most closely approximates the requirements.

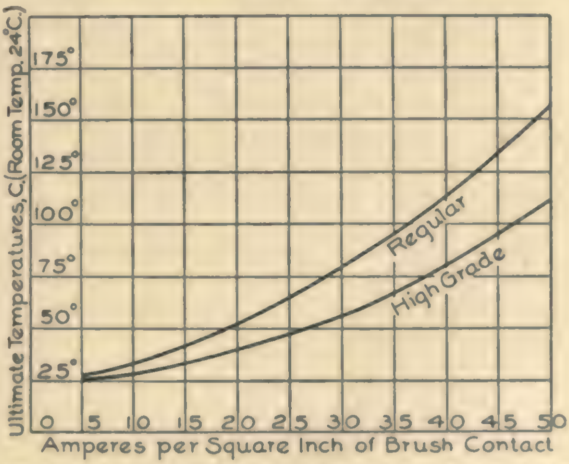


Fig. 145.—Average Temperature Curves of Standard Grades of Carbon or Graphite Brushes.

Heating of Carbon Brushes. Fig. 145 gives the variation of the temperature-rise of two well-known grades of carbon brushes with increase in the current-density employed. The room temperature at the time of the test was about 24° C., so that the values on the curves represent final or total temperatures. It is therefore necessary to deduct 24 from the values given by these curves, to realize the actual temperature-rise.

TABLE VIII

Standard Sizes of Carbon Brushes

Length Width Thickness	Length Width Thickness	Length Width Thickness	Length Width Thickness	Length Width Thickness	Length Width Thickness	Length Width Thickness
2½x2¼x ¼	3 x 1 x ¼	3½ x 1 x ¼	4 x 1 x ¼	5 x 1 x ¼	6x1½x ½	7x1½x ½
2½x2¼x ½	3 x 1 x ½	3½ x 1 x ½	4 x 1 x ½	5x1½x ¼	6x1½x ¾	7x2 x ½
2½x2¼x ¾	3 x 1 x ¾	3½ x 1 x ¾	4 x 1 x ¾	5x1½x ½	6x1½x1	7x2¼x ½
2½x2¼x1	3 x 1 x 1	3½ x 1 x 1	4 x 1 x 1	5x1½x ¾	6x1½x1¼	7x2½x ½
2½x2 x ½	3x1½x ¼	3½ x 2 x ¼	4x1½x ¼	5x1½x1	6x1½x1½	7x2½x ⅜
2½x2½x ¼	3x1½x ½	3½ x 2 x ½	4x1½x ½	5x1½x1½	6 x 2 x ½	7x2½x ⅝
2½x2½x ½	3x1½x ¾	3½ x 2 x ¾	4x1½x ¾	5 x 2 x 1	6x2½x ¾	7x2¼x ⅜
2½x2½x ¾	3x1½x1	3½ x 2 x 1	4x1½x1	5 x2 x 1¼	....	7x2¼x ⅝
2½x2½x1	3 x 2 x ¼	3½ x 3 x ¼	4 x 2 x ¼	5x2½x ¼	....	7x2¼x ¾
....	3 x 2 x ½	3½ x 3 x ½	4 x 2 x ½	5x2½x ½	....	7x2¼x ⅞
....	3 x 2 x ¾	3½ x 3 x ¾	4 x 2 x1⅜	5x2½x1	....	7x2¼x1
....	3 x 2 x 1	3½ x 3 x 1	....	....	....	7x2¼x1½
....	3 x 3 x ¼	3½x3½x ¼	....	....	....	....
....	3 x 3 x ½	3½x3½x ½	....	....	....	....
....	3 x 3 x ¾	3½x3½x ¾	....	....	....	....
....	3 x 3 x 1	3½x3½x 1	....	....	....	....
....	....	3½x3½x1½	....	....	....	....

CALCULATIONS OF MECHANICAL PARTS

General. The almost invariable practice is to have the magnet-yoke of a generator or motor serve as a frame for all the remaining parts, except in larger sizes, for which independent bearings are used. The strength of the material used in the field-ring is great, and as its bulk is large in comparison with the load sustained, it is rarely that mechanical calculations are made. In the case of the armature shaft, the arms or spokes for the spider, and the bearings, however, calculations are necessary, which will now be briefly considered.

Armature Shafts. The shafts of armatures are usually made of mild steel; and for their design, reference may be made either to standard works on machine design or to the formulæ below, based on the usual methods employed in that class of work, and modified to meet the requirements of electrical machinery. Shafts for the latter are generally made somewhat larger than for other machines, on account of the magnetic pull which comes upon the shaft when the armature is even slightly out of center of the poles, as already noted.

The diameter of that portion of the shaft within the armature core, Fig. 146, may be found from the following expression,

$$d_c = k_1 \sqrt[4]{\frac{W}{\text{r. p. m.}}},$$

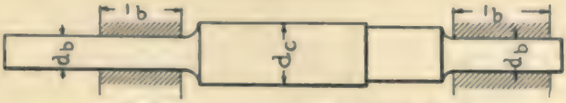


Fig. 146. Dimensions of Armature Shaft.

in which

d_c = Shaft diameter within the core, in inches;

k_1 = A constant depending upon the output of the machine as given in Table IX;

W = Output of the machine in watts.

The shaft diameter in the bearing or journal, may be computed from the following formula,

$$d_b = k_2 \sqrt{W} \sqrt[4]{\text{r. p. m.}}$$

in which

d_b = Diameter of the shaft in the bearing;

k_2 = A constant depending upon the speed of the machine (see Table X).

TABLE IX

Value of Constant in Formula for Diameter of Core Portion of Shaft

Capacity of Machine (in Kilowatts)	Value of k_1
Up to 1 kilowatt	1
1– 5 "	1.1
5– 10 "	1.2
10– 50 "	1.3
50– 100 "	1.4
100– 200 "	1.5
200– 500 "	1.6
500–1,000 "	1.7
1,000–2,000 "	1.8

TABLE X

Value of Constant in Formula for Diameter of Shaft in Bearing

Type of Armature	Value of k_2
High-speed drum armature	0.0025
High-speed ring armature	0.003
Low-speed drum armature	0.004
Low-speed ring armature	0.005

Armature Spider Spokes. Drum armatures in which the core consists of a ring of iron supported by means of a skeleton pulley or spider attached to the shaft, the winding being placed in slots in the circumference of the core, are called *ring-core* armatures, to distinguish them from *ring-wound* armatures such as shown in Fig. 30. Fig. 147 represents a ring-core, drum-wound armature in process of construction. In both cases the driving of the armature is effected by a number of spokes which respectively form part of the spider itself (Fig. 148) or of a separate frame keyed to the skeleton pulley (Fig. 149). The spokes are usually elliptical in cross-section, and are generally made of cast iron or steel. They should be designed adequately to support and drive the armature.

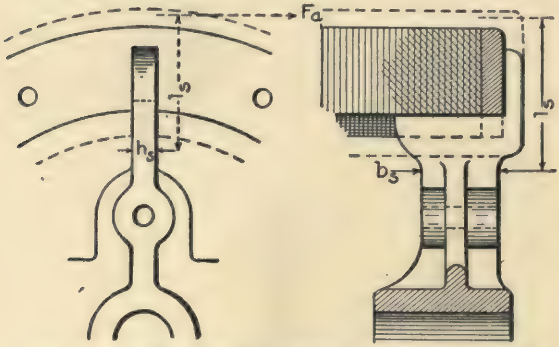


Fig. 147. Ring-Core Drum-Wound Armature in Process of Construction.

From a consideration of the bending and shearing moments acting upon such an arm or spoke (Fig. 149), it may be shown* that:

$$\frac{\pi\, b_s\, d_s^{\,2}\dagger}{32} \leqq \frac{100\, w\, l}{r\, n_s \text{ r. p. m.}} \cdot \frac{1}{f_t};$$

and,

$$b\, d \leqq \frac{100\, w\, l}{r\, n_s \text{ r. p. m.}} \cdot \frac{1}{f_s},$$

in order that the safe working stresses of the material utilized may not be exceeded. In these formulæ,

b = Breadth of an arm parallel to the shaft, in inches;

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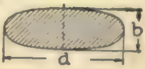
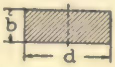
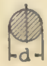
*See "The Dynamo," by Hawkins & Wallis, New York, 1903; p. 310.

† $\frac{\pi b_s d_s^2}{23}$ is known as the *modulus of resistance* of the section  For the section  it is $\frac{b_s d_s^2}{6}$; for the section  it is $\frac{\pi d^3}{32}$; and if any one of these sections be used, the corresponding section modulus should be substituted in the formula.

f_s = Safe working stress of the material for shearing, in lbs. per sq. in., which, for cast iron, is 5,000, and for cast steel 15,000;

f_t = Safe working stress of the material for tension or compression, in lbs. per sq. in., which is 1,250 for cast iron, and 5,000 for cast steel;

d = Thickness of the arm, in inches;

l = Distance from the tip of section whose breadth is b_s and whose thickness is d_s.

n_s = Number of spokes or arms;

r = Radius of an arm, in inches.

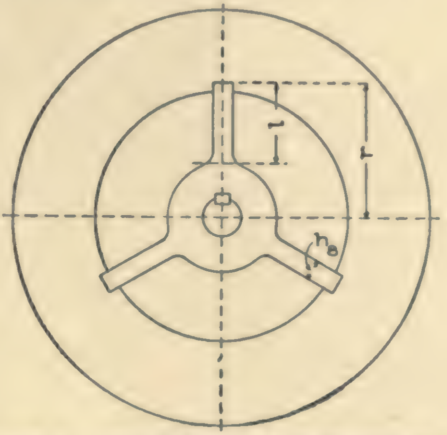


Fig. 148. Armature Driven by Spokes Forming Part of Spider.

Armature Binding Wires. In the case of toothed armatures, the conductors must be held in the slots. For this purpose it is customary to use wedges driven in under the tops of the teeth, or, in the case of straight teeth, to use a number of external bands known as *binding wires*. These must be strong enough to resist the centrifugal forces, and yet at the same time occupy very little radial depth, that they may not interfere with the clearance between the armature and the pole-faces. The almost invariable practice is to use a tinned wire of hard-drawn brass, phosphor-bronze, or steel, which, after winding, can be sweated together into a solid band. The ultimate tensile strength of phosphor-bronze is from 65,000 to 120,000 pounds per square inch, while that of steel wire varies from 120,000 to 250,000 pounds per square inch, the larger figures relating to the smaller sizes of wire.

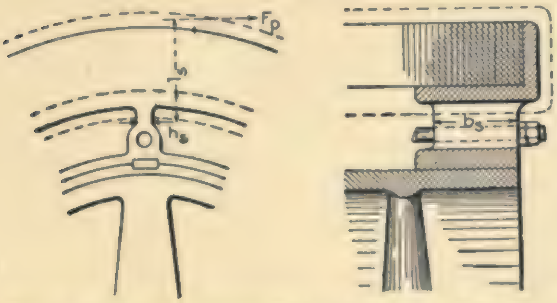


Fig. 149. Ring-Core Armature Driven by Pulley and End-Rings.

To estimate the proper size and number of binding wires required, we have that if d be the diameter (in inches) of the circular path described by a mass of weight w_1 pounds, the centrifugal force will be $= 0.0000143 \times d \times w_1 \times \overline{\text{r. p. m.}}^2$ pounds weight. So that if we assume a value of 100,000 pounds per square inch as the maximum allowable tensile stress in steel or phosphor-bronze wire, and allow a safety factor of say 10, the total section of binding wire required will be:

$$= \frac{0.0000143 \times 10 \times w_1 \times Z \times d \times \overline{\text{r. p. m.}}^2}{\pi \times 100{,}000}$$

$$= 4.55 \times 10^{-10} \times w_1 \times Z \times d \times \overline{\text{r. p. m.}}^2 \text{ square inches.}$$

From this total necessary section, and an appropriate wire table, the number of wires is then calculated, and they are then arranged in suitable belts.

Example. Let $w_1 = 0.39$ lb.; $Z = 1{,}536$; $d = 62$ in.; r. p. m. $= 150$. The total necessary section computed by the above formula is 0.379 square inch. Referring to the wire gauge tables, we find that 148 wires of No. 15 B. & S. gauge will fulfil the conditions. These may be arranged as follows: 5 belts of 16 wires each over the core body, and 4 belts of 17 wires each over the extended ends of the winding (*i.e.*, 2 belts of 17 wires each over each end).

Under each belt of binding wires, it is usual to lay a band of insulation. These bands generally consist of two layers, first a thin strip of vulcanized fibre or of hard red varnished paper slightly wider than the belt of wires, and then a strip of mica (in short pieces) of about equal width. Sometimes small straps of thin brass are laid under each belt of binding wires, having tags which can be turned over and soldered down to prevent the two ends of the binding wire from flying out.

Armature Bearings. Bearings for generators and motors should be very strong and rigid, with ample wearing surface, in order that the armature may not become materially displaced with respect to the poles as a result of magnetic attraction as well as weight, and also to prevent overheating of the journals. The following formula takes into account the increased generation of heat at higher peripheral velocities, and also provides sufficient wearing material:

$$l_b = k_3 \times d_b \sqrt{\text{r. p. m.}},$$

wherein

l_b = Length of the bearing, in inches;

d_b = Diameter of the shaft in the bearing (from page 129);

k_3 = A constant dependent upon the speed of the armature (given in Table XI).

TABLE XI

Value for Constant in Formula for Length of Armature Bearing

Capacity of Machine (in Kilowatts)	High-Speed Armatures	Low-Speed Armatures
Up to 5 kilowatts	0.1	0.15
" 10 "	0.1	0.175
" 50 "	0.125	0.200
" 100 "	0.150	0.225
" 500 "	0.175	0.250
" 1,000 "	0.200	0.275
" 2,000 "	0.225	0.300

Losses Due to Friction in the Bearings and to Windage. These are very difficult to predetermine with even reasonable accuracy. Designers usually estimate them from previous experience. For belt-driven machines ranging in speeds from 1,800 r. p. m. to 300 r. p. m. and of capacity from 30 to 500 kw., these losses should range from 3 per cent of the output in the smaller machines to 1 per cent in the larger sizes. For direct-connected generators, this figure ranges from 1 per cent to 0.4 per cent of the output, depending upon the size and speed, being lower for machines of this type on account of the lowered r. p. m. and the better alignment.

Calculation of Efficiency. On page 63, efficiency was defined as the ratio between output and input of the machine. It may also be defined as the ratio between the output and the output *plus* the losses. These latter come under the following heads, the computation of each having been considered in the foregoing pages:

(1) *Copper Losses.* These consist of the sum of the I^2R losses in the armature field-coils, and increase as the square of the current—being, however, independent of the speed.

(2) *Iron Losses.* These are made up of the eddy-current and hysteresis losses produced in the armature core-plates owing to the changes in flux-polarity and density to which they are periodically subjected. They vary slightly with load, on account of the strained distribution produced, and are always variable with the speed, eddy currents varying as the square of the speed, and hysteresis losses as the 1.6th power of the speed.

(3) *Excitation Losses.* These consist of the watts expended as heat and utilized to drive the magnetizing current around the magnetizing coils, and are included in machine I^2R losses.

(4) *Commutator Losses.* These losses may be subdivided into:

(*a*) I^2R loss due to brush-contact resistance;

(*b*) Brush friction loss.

(*c*) Losses through sparking and through eddy currents in the commutator bars.

Of those, *a* and *b* are the only ones usually considered, the other being practically negligible except in generators furnishing very large currents at very low voltages.

(5) *Bearing Friction and Windage Losses.* The former are the losses due to the friction of the shaft in the bearings, and depends only upon the load and speed. The latter are occasioned by the armature churning the air, and are independent of the load, but vary with the speed.

(6) *Secondary Copper and Iron Losses.* These have already been considered as eddy-current loss in the armature conductors, eddy-current loss in the pole-faces, etc.

The method of calculating each of these losses has been considered in detail above, so that we have,

$$\eta = \frac{w_0}{w_0 + w_1 + w_2 + w_3 + w_4 + w_5 + w_6},$$

wherein w_0 is the output of the machine in watts, and w_1, w_2, w_3, etc., represent the losses in watts just enumerated. Representative curves of these losses are shown on pages 15 and 123; while Table XII. gives the average efficiencies and apportionment of losses of direct-driven machines of various sizes.

TABLE XII

Average Efficiencies and Apportionment of Losses of Direct-Driven Machines of Various Sizes

Output of Machine (in kw.)	Commercial Efficiency (per cent)	Percentage Losses In				
		Armature		Field	Commutator,	Friction and Windage
		Copper	Iron	Copper	Friction and Drop	
1	80	4.3	3.7	8	0.6	3.4
2	82	4.0	3.4	7	0.57	3.03
5	84	3.7	3.1	6	0.54	2.68
10	86	3.4	2.8	5	0.50	2.30
20	88	3.1	2.5	4	0.46	1.94
30	89.5	2.8	2.2	3.5	0.42	1.58
50	91.0	2.5	1.9	3.0	0.39	1.21
100	92.0	2.2	1.6	2.75	0.37	1.08
200	93.0	1.9	1.4	2.50	0.35	0.85
300	93.5	1.7	1.35	2.35	0.33	0.77
500	94.0	1.6	1.25	2.15	0.31	0.69
1,000	95.0	1.45	1.10	1.65	0.29	0.51
2,000	96.0	1.30	1.00	1.10	0.27	0.33

In using this table, it must be borne in mind that the values may vary considerably, even in machines of the same output but of different speeds and voltages, and under different conditions of working. The figures given should be used merely as a guide in apportioning or checking the losses.

Calculation of Magnetization Curve and Voltage Drop.—*Predetermination of Magnetization Curve.* The magnetization curve of a dynamo-electric machine is the curve connecting the ampere-turns upon the magnetic circuit, and the useful flux produced by them in the armature teeth. Since the number of turns upon the field coils is usually constant, and since the no-load terminal voltage of a generator is directly proportional to the useful flux entering the teeth of the armature, it is more convenient to represent the magnetization curve by the relation between the field-exciting current in amperes, and the no-load terminal voltage. This curve is generally predetermined by calculation, and then actually tested in the finished machine for each new type, thus checking the correctness of the designer's assumptions. The experimental determination is explained later. These curves are valuable, not only to show the character of one particular machine, but are useful for comparing different ones. For this purpose a standard ratio of the scales on which the curves are based should be followed.

To illustrate the method of constructing the magnetization curve of a continuous-current generator, let us consider the case of a generator the dimensions and particulars of which are as follows:

GENERAL:	
Rated load output in kilowatts	150
Terminal voltage at rated load	250
External current, in amperes, at rated load	600
Armature speed, in r. p. m.	450
Number of poles	6
ARMATURE DIMENSIONS:	
External diameter of core, in inches	33
Internal " " " " "	18
Number of slots	124
Depth of each slot, in inches	1.625
Width " " " " "	0.400
Pitch of slot at armature face, in inches	0.840
Radial depth of iron in core under teeth, in inches	5.875
Total length of core, in inches	11.
Iron length of core, in inches	9.
Number of conductors	496
Style of winding	parallel
Bare dimensions of each conductor, in inches	0.7 by 0.11
Insulated dimensions of each conductor, in inches	0.73 by 0.14
Mean length of one armature turn, in inches	66

Field-Magnet Data:	
Number of poles	6
Diameter of bore, in inches	33.625
Turns per pair of poles	3,602
Shunt exciting current, in amperes	4.10
Angle covered by each pole-face, in degrees	43
Commutator Dimensions:	
Diameter, in inches	21
Number of segments	248
Active length, in inches	7.5

The magnet-cores are of steel, circular in cross-section and bolted to the yoke, the pole-shoes being in one piece with the magnet-cores. The field frame is cast in two pieces and bolted together. All the field-exciting coils are connected in series. The armature slots are parallel-sided, of the dimensions stated above. There are two ventilating apertures in the core, each $\frac{3}{8}$ inch wide. The armature winding has six circuits in parallel, with six sets of brushes set 60° apart.

In order to construct the magnetization curve, we have:

$$E = \frac{\phi_a \times Z \times \text{r. p. m.}}{60 \times 10^8} \quad \text{(see page 62.)}$$

$$= \frac{496 \times 450}{60 \times 10^8} \times \phi_a$$

$$= 0.00000372\ \phi_a$$

As the leakage coefficient of this machine is $\nu = 1.11$ (from Table II, page 77), we may construct the following table, since $\phi_m = \nu\,\phi_a$ (from page 76):

E	ϕ_a	ϕ_m
200	5,370,000	5,960,000
230	6,170,000	6,850,000
260	6,980,000	7,750,000
280	7,510,000	8,350,000
300	8,050,000	8,940,000

From the drawings we find:

Mean length of magnetic path in magnet-yoke, in inches	26
“ “ “ “ “ “ two magnet-cores, in inches	28
“ “ “ “ “ “ armature core, in inches	15
“ “ “ “ “ “ two teeth, in inches	3.25
“ “ “ “ “ “ two air-gaps, in inches	0.625
Magnetic area of yoke, in square inches	44
“ “ “ magnet-cores, in square inches	78.5
“ “ “ armature body, in square inches	53

The polar angle being 43°, we have, for the number of teeth under one pole:

$$\frac{124 \times 43^\circ}{360^\circ} = 14.7.$$

Allowing for spreading of flux in the air-gap owing to high flux-density in the teeth, we may take 16 teeth as receiving flux from each pole.

As the pitch of slots at the bottom of the slots is $\frac{93.45}{124} = 0.754$ in., and as the slots are 0.4 inch wide, we have as the width of a tooth at its root, $0.754 - 0.400 = 0.354$ inch. The area of the teeth receiving flux from each pole will therefore be:

$$16 \times 0.354 \times 9 = 51 \text{ square inches,}$$

since the length of iron in the armature parallel to the shaft is 9 inches.

The air-gap area, taken as the pole-face area, is 140 sq. in.

This completes the data necessary for computation of the magnetization curve, and it is sufficient here to calculate a few points on this curve, as the method is the same for all.

Considering the machine to generate an e. m. f. of 200, 230, 260, 280, and 300 volts respectively, we obtain from the previous table, by the method explained on page 82, the accompanying tabulation (page 138).

As seen from this tabulation, we have:

$E = 200$, Ampere-turns per pair poles = 8,715
$E = 230$, “ “ “ “ “ = 10,846
$E = 260$, “ “ “ “ “ = 13,833
$E = 280$, “ “ “ “ “ = 16,498
$E = 300$, “ “ “ “ “ = 19,095

By plotting the curve connecting these five points, we obtain the working portion of the magnetization curve shown in Fig. 150. The complete magnetization curve may similarly be computed for the full range of the field-exciting current, taking account of the residual magnetism of the magnetic circuit; but in the design of generators, the working portion is sufficient.

It is usual to operate shunt-wound generators upon that portion of the magnetization curve just above the so-called bend, while compound-wound machines are usually designed to operate near the bend of the magnetization curve.

Computation of Voltage Drop from Magnetization Curve. At any generator load, there are four causes tending to lower the voltage at the terminals of the machine—namely, ohmic resistance of the armature and series coils (if any), drop due to brush contact, demagnetizing action of the armature, and distortion of the armature flux.

APPLICATIONS OF MAGNETIZATION CURVE CALCULATIONS

Portion of Magnetic Circuit	Material	Mean Length of Magnetic Path (Inches)	Magnetic Area (Square Inches)	$E = 200$ $\phi_a = 5{,}370{,}000$ $\phi_m = 5{,}960{,}000$			$E = 230$ $\phi_a = 6{,}170{,}000$ $\phi_m = 6{,}850{,}000$			$E = 260$ $\phi_a = 6{,}980{,}000$ $\phi_m = 7{,}750{,}000$			$E = 280$ $\phi_a = 7{,}510{,}000$ $\phi_m = 8{,}350{,}000$			$E = 300$ $\phi_a = 8{,}050{,}000$ $\phi_m = 8{,}940{,}000$		
				Flux-Density	Ampere-Turns per Inch Length	Ampere-Turns	Flux-Density	Ampere-Turns per Inch Length	Ampere-Turns	Flux-Density	Ampere-Turns per Inch Length	Ampere-Turns	Flux-Density	Ampere-Turns per Inch Length	Ampere-Turns	Flux-Density	Ampere-Turns per Inch Length	Ampere-Turns
Magnet-Yoke...	Cast Steel	26	2x44	67,800	12.5	325	77,900	18	468	88,000	25.5	663	94,900	37	962	101,500	56	1,455
2 Magnet-Cores.	do	28	78.5	76,000	16.5	462	87,200	25.0	700	98,600	47	1,315	106,200	76	2,125	113,900	107	2,995
2 Air-Gaps......	Air	0.625	140	38,400	120,100	7,503	44,100	13,800	8,630	49,900	15,600	9,750	53,700	16,800	10,500	57,500	18,000	11,250
2 Teeth..........	Sheet Steel	3.25	51	*105,000	119	387	*117,500	305	991	*130,500	625	2,030	*137,500	830	2,798	*144,000	998	3,222
Armature Core.	do	15	2x53	50,600	2.5	38	58,300	3.8	57	65,900	5	75	71,000	7.5	113	76,000	11.5	173
Ampere-turns per pair of poles.......				......	......	8,715	......	......	10,846	......	......	13,833	......	.....	16,498	......	......	19,095

* Corrected as per curves on page 81.

The voltage-drop due to resistance of the armature winding, series field-coils, and brush contacts, is:

$$e = I_a r_a + I_a r_{se} + I_a r_b,$$

omitting the second term if the series winding is absent. Then, in the assumed case (Fig. 150), the no-load e. m. f. being 250, represented by *P* on the magnetization curve, the rated-load current being 600 amperes, and the resistance of the main circuit (including brushes, armature winding, and series field-winding) being 0.00893 ohm, we have:

$$e = 0.00893 \times 600 = 5.4 \text{ volts},$$

which, added to 250, shows that the generated e. m. f. at rated load would have to be 255.4 volts, without considering armature reaction. This is represented by the point *O* on the saturation curve; hence 13,500 ampere-turns are required to generate this e. m. f. In other words, at rated load and speed, assuming the terminal voltage to remain the same as at no load, we require 13,500 ampere-turns upon the field, assuming armature reaction absent.

As it is often convenient to check the dimensions of an armature conductor in a preliminary design by means of this voltage-drop, Table XIII is herewith given:

TABLE XIII

Voltage-Drop as Related to Output in Shunt and Compound Machines

OUTPUT OF MACHINE (in kilowatts)	VALUE OF e AS A PERCENTAGE OF RATED-LOAD TERMINAL e. m. f.	
	SHUNT MACHINES	COMPOUND MACHINES
5	7	10
10	6	8
25	5	7
50	4	6
100	3.5	5
200	3	4
500	2.5	3
1,000	2	2.5
2,000	1.5	2

With regard to the demagnetizing ampere-turns of the armature, we know that in general these are the ampere-turns lying within twice the angle of brush lead. Assuming the brushes to be set just under the pole-tips at rated load, the demagnetizing ampere-turns will be the number of armature conductors lying between adjacent pole-corners, multiplied by the current in them.

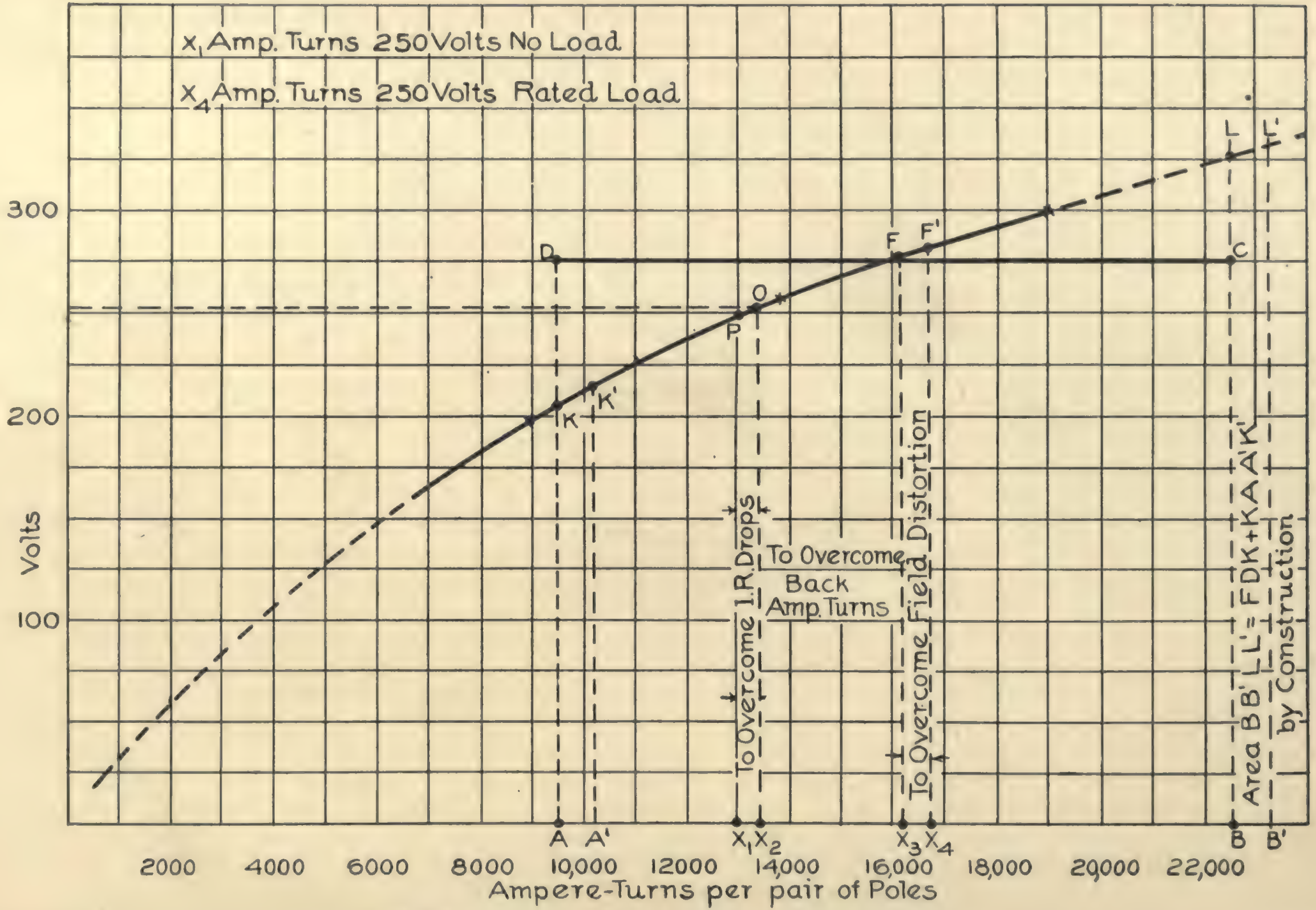


Fig. 150. Magnetization Curve of a Continuous-Current Generator.

These ampere-turns are multiplied by the leakage coefficient (because they have to be neutralized by the field-winding); the result is added to X_2, and set off on the diagram as X_3 (Fig. 150). By projecting this up to the curve, the point F is obtained, which corresponds to the necessary e. m. f.

Example. In the case previously considered, the number of slots lying between pole-tips is,

$$\frac{60^\circ - 43^\circ}{360^\circ} \times 124 = 5.8;$$

and in each slot there are four conductors, each carrying 100 amperes at rated load. Hence the demagnetizing ampere-turns of the armature at rated load per pole (assuming that the brushes are moved right under the pole-tips, and that the leakage coefficient is 1.17), are:

$$5.8 \times 4 \times 100 \times 1.17 = 2{,}715.$$

Adding these ampere-turns to X_2, we get $X_3 = 16{,}200$ as the total ampere-turns required at rated load, assuming that there is no drop in voltage caused by diminished permeability in the teeth at the forward pole-horn due to distortion of the flux.

With a smooth-core armature, the flux distortion in the air-gap does not produce a diminution in the terminal voltage of the machine; but with toothed armatures, allowance must be made. In Fig. 151, let AB represent the width of the pole-face to scale, and EF the flux-density in the air-gap B_g. Then the area $ABCD$ is proportional to the useful flux ϕ_a, and at no-load we may regard this flux as being uniformly distributed along the air-gap as indicated by said rectangle. Assuming the permeability of the teeth to be constant, and laying off AH as the flux-density at the hindward pole-horn, and BG as the flux-density at the forward pole-horn (the flux being heaped up in the latter at rated load, and withdrawn from the former), the line HFG would represent the flux-density variation from point to point in the air-gap, and the area $AHGB$ would be equal to the area $ABCD$, since the permeability of the air-gap is constant. But the increased flux-density at the forward pole-horn causes the permeability of the teeth at this point to have a much lower value than it has with the flux-density B_g,

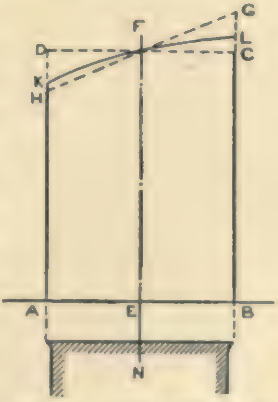


Fig. 151. Curve Showing Relation between Pressure Drop and Flux-Distortion in Air-Gap.

while, on the other hand, the permeability of the teeth under the hindward pole-horn has increased on account of the diminished flux-density in them. As a result, the line *HFG* takes the bent form shown by the curve *KFL*, and the *shape of this curve is the same as that of the magnetization curve over this range.* As can readily be seen from the figure, the area *AKLB* is considerably less than the area *AHGB;* that is, there is a diminution of the useful flux ϕ_a, and consequently a corresponding voltage drop, which will as a rule be greater, the higher the flux-density in the teeth.

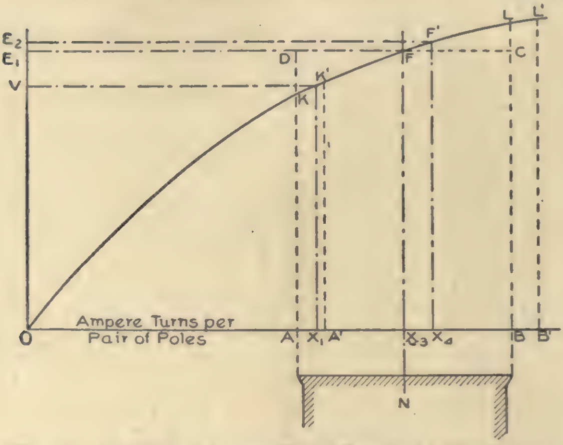
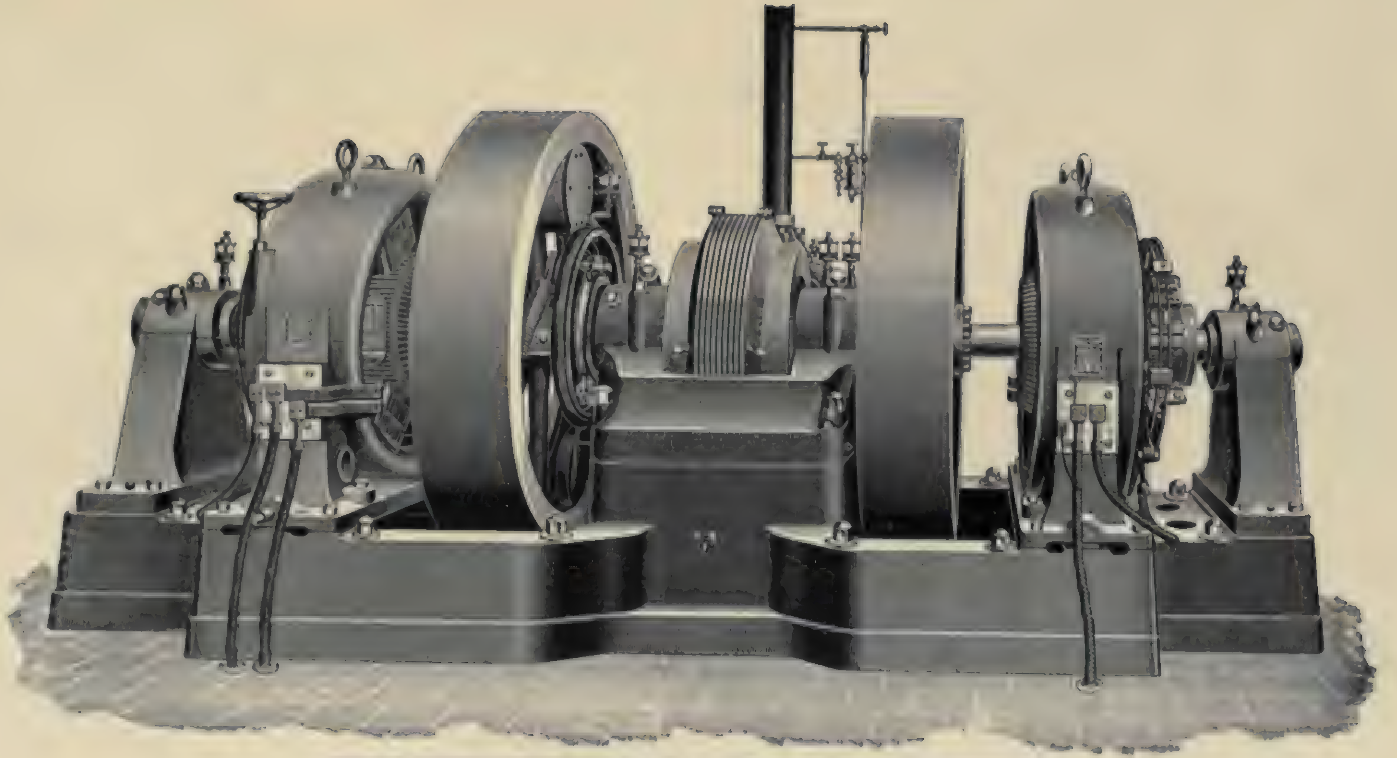


Fig. 152. Calculating Ampere-Turns Required to Compensate for Distortion of Useful Field.

One way to estimate the number of ampere-turns needed to compensate the effect produced by the distortion of the useful flux, is as follows:

In Fig. 152, let *OL* be the magnetization curve of the machine, the ampere-turns required for no-load, and those for rated-load induced e. m. f. at no load (and, therefore, without the extra allowance for distortion) being set off upon its scale of abscissæ *OX*, as X_1 and X_3, respectively, these having been estimated as shown in Fig. 150. Now, upon *OX*, mark off *OA* and *OB* as shown in the figure. The point *A* then represents the hindward pole-horn, and the point B the forward pole-horn. Had the distortion been absent, the ampere-turns required to produce E_1 volts would have produced a flux across the gap proportional to the area of the piece *ABCD*. But, as the distortion is present, the flux is proportional to the smaller area *ABLK*. Hence, we shift the point *F* higher up the curve to a point such as *F'*, so that the area *A'B'L'K'* equals the area *ABCD*. This gives a new point X_4 along *OX*, representing the rated-load ampere-turns required. Consequently, for a compound-wound machine, the series ampere-turns



ENGINE DIRECT-CONNECTED WITH TWO WESTINGHOUSE GENERATORS.

Ames Iron Works.

must be $X_4 - X_1$, and the shunt ampere-turns X_1, in order that the terminal volts may be OV at rated load. If the machine is shunt-wound, the resistance of the shunt rheostat must be capable of reducing X_4 ampere-turns to X_1 ampere-turns. And if there are to be neither series turns nor shunt regulator, the drop from rated load to no load would be $OE_2 - OV$ at constant speed.

Applying this reasoning to the machine under consideration, we have, for the ampere-turns under one pair of poles:

$$\frac{47°}{360°} \times 124 \times 4 \times 100 = 6{,}500.$$

The first factor being the slots under each pole, the second the number of inductors per slot, and the third the current per inductor, we set off, therefore, 6,500 ampere-turns on each side of the point X_8 (Fig. 150), and obtain thus the points A and B, which represent the hindward and forward pole-horns respectively. If the distortion of the main flux were absent, the area of the rectangle $ABCD$ would be proportional to it. But as this is not so, it is proportional to the smaller area $ABLK$. In order to make this latter area equal to that of the rectangle, we must shift the point F higher up on the curve to the position F', so that area $A'B'L'K'$ = area $ABCD$. In this manner we obtain the point X_4 as the necessary ampere-turns at rated load. Its value is: $X_4 = 16{,}800$.

The method just discussed for predetermining the series (compound) winding needed to give constant terminal e. m. f. at all loads between zero and rated load, may easily be extended to the case of over-compounding, by adding to the calculated voltage-drop in the machine the required increase in terminal voltage.

This method, although one of the most satisfactory, does not permit of great accuracy; but fortunately this is not important. By designing the shunt regulator liberally, and by placing a shunt across the series field-coils, the desired result may be reached by trial. This is in fact the practice of almost all dynamo builders.

The possible discrepancies between calculations thus made and results of actual test, are shown by the following values of the ampere-turns required at no-load and at rated load, as determined by the manufacturers of the machine we have been discussing:

Output	Calculated Values	Actual Values
No-load	13,400	13,000
Rated-load	16,800	15,300

The difference was caused, no doubt, by the fact that better quality of iron was used in the machine than that for which the ampere-turns were computed.

EXPERIMENTAL DETERMINATION OF CHARACTERISTIC CURVES OF CONTINUOUS-CURRENT GENERATORS

Dr. John Hopkinson, in 1879, first suggested that the behavior of a generator could best be studied from a curve representing the relation between the e. m. f. and current of the machine at different loads. In 1881, M. Marcel Deprez elaborated Hopkinson's method and gave the name of *characteristics* to these curves.

At present the characteristics most commonly developed are:

(1) Magnetization curve.

(2) External characteristic.

(3) Curve of flux distribution (explained on page 39).

Experimental Magnetization Curve. The method of predetermining the magnetization curve of any continuous-current generator was explained on page 135.

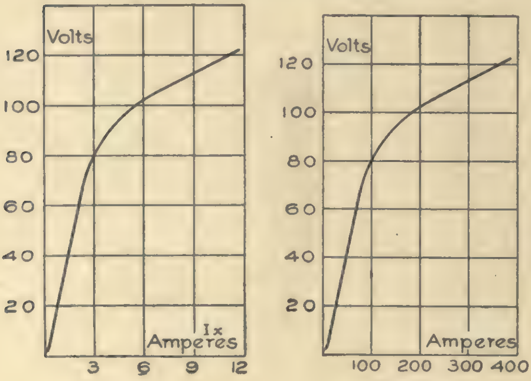


Fig. 153. Fig. 154.

Curves Showing Effects of Residual Magnetism on the Magnetization Curve of a Dynamo.

The magnetization curve of a dynamo, however, can be determined experimentally by driving it at rated speed, and observing the voltage at the terminals for different values of the current sent through the field-winding from some outside source. Figs. 153 and 154 are typical magnetization curves of a 30-kw. generator; Fig. 153 shows the magnetization curve of the machine when its field is wound with many turns of fine wire (*i.e.*, a shunt dynamo); and Fig. 154 shows the magnetization curve of the same machine when its field is wound with a few turns of coarse wire (*i.e.*, a series dynamo).

Dependence of the Magnetization Curve upon Speed. When the magnetization curve of a dynamo has been determined for a given speed (n), the curve for any other speed (n') can be found by multiplying the ordinates of the given curve by $n' \div n$. This is evident when we consider that the flux ϕ_a has a definite value for each value of field current, so that the generated e. m. f. is proportional to the speed.

Effect of Residual Magnetism. When the field-exciting current of a generator is zero, the flux in the armature is in general *not* zero, on account of residual magnetism. This effect is indicated in Figs. 153 to 155, for it is seen here that when the field-exciting current is zero, the generated e. m. f. has a definite value.

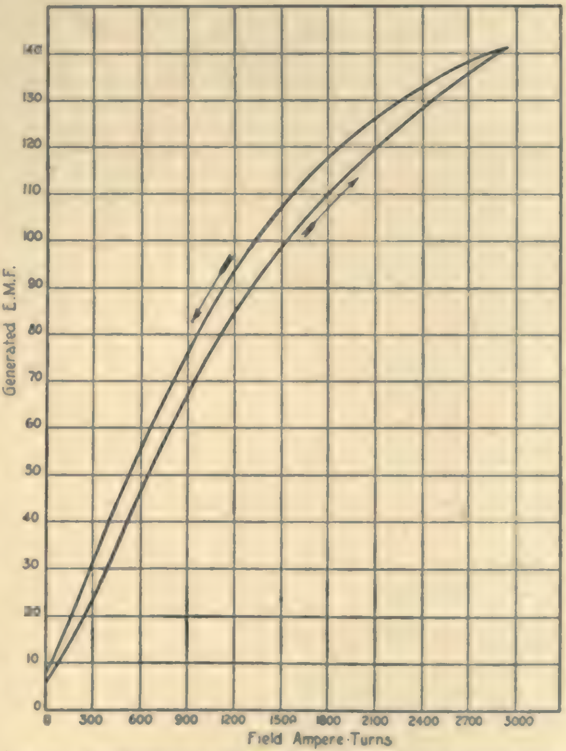


Fig. 155. Magnetization Curves of a Dynamo with Increasing and Decreasing Field-Current

Effect of Hysteresis. On account of hysteresis in the iron portions of the magnetic circuit, the flux in the armature, and hence the no-load terminal voltage, corresponding to a given value of the field-exciting current, is smaller when the latter is increasing than when it is decreasing. Therefore the magnetization curve of a dynamo for increasing field-current, is slightly lower than that for decreasing field-current, as shown in Fig. 155. This effect of hysteresis upon the magnetization curve of a generator is usually ignored in discussing the relation to other characteristic curves. In fact, the effect of hysteresis is greatly diminished in practical operation, inasmuch as the mechanical vibrations of the machine and the slight pulsations of armature and field currents, cause the flux to settle to a normal value.

External and Other Characteristic Curves. The external characteristic curve of any dynamo-electric machine is a curve representing the relation between the terminal voltage of the machine and the external load in amperes. Besides the external characteristic curve, the *total characteristic curve*, and the *ampere-ohm characteristic curve* are sometimes considered. The former represents graphically the relation between the generated e. m. f. of the machine and the armature current, while the latter shows the relation between output of the machine in amperes and resistance of the external circuit.

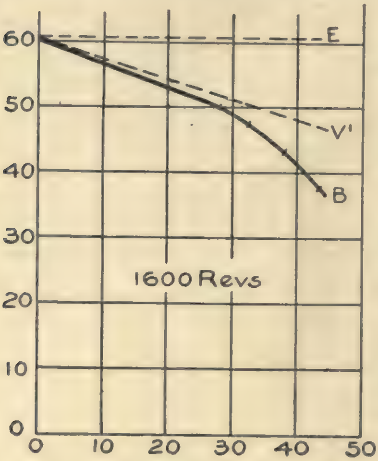


Fig. 156. Characteristic Curve of Separately-Excited Dynamo.

Inasmuch as the characteristic curves of the series, shunt, and compound generators differ markedly from one another, those pertaining to each type will be considered separately.

Characteristic Curves of Magneto and Separately-Excited Machines. In the magneto machine, the permanent magnetism of the steel may be considered approximately constant, and the same condition would obtain in a separately-excited machine if the field-current were kept constant. Owing, however, to the reactions of the armature when the current flows therein, the useful flux and terminal voltage are decreased. In Fig. 156 are given the results of tests upon a separately-excited dynamo. The line *E* represents the generated e. m. f. of the machine when operated on open circuit at rated speed and field-current. The line *V′* shows the terminal voltage which would be obtained if armature reactions were absent, and only armature and brush drop were in evidence. The curved line *B* represents the actually observed values of the terminal voltage when different currents were drawn from the machine. The pronounced droop at the lower end of the latter curve is probably due to the greater demagnetizing effect when there is a considerable lead at the brushes.

The characteristic shows such a downward curvature more definitely when the field-magnets are weakly excited.

Characteristic Curves of Series-Wound Machines. The characteristic curve of a series generator may be determined experimentally by driving the machine at constant speed, and observing corresponding values of current output and terminal voltage for different resistances in the external circuit.

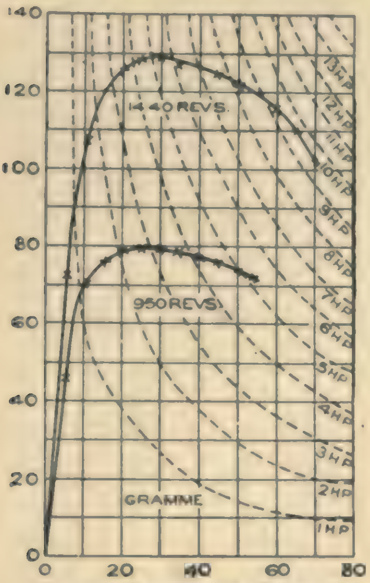


Fig. 157. Characteristic Curves of a Series-Wound Generator at Different Speeds.

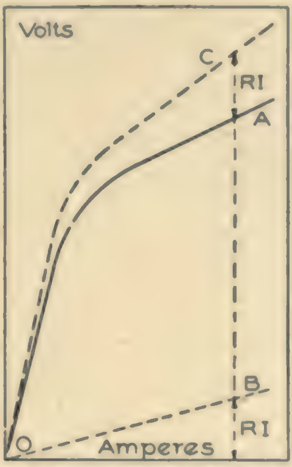


Fig. 158. Effect of Residual Magnetism on Characteristic Curve of a Series-Wound Generator.

External Characteristic Curve. Fig. 157 represents the external characteristic curves of an "A" Gramme machine, series-wound, at two different armature speeds. As is seen from the shape of the curves, the e. m. f. increases at first with the current, due to the increase in magnetization of the field-magnets. As the parts of the magnetic circuit, with increase of load, approach saturation, the reactions of the armature and I R drops become of relatively greater importance; the result is that the curve flattens out and finally bends downward.

Total Characteristic Curve. The total characteristic curve shown in Fig. 158 was plotted from the external characteristic in the following manner: Knowing that,

$$E^{*} = V + (r_a + r_{se} + r_b)\, I_a = V + R\, I_a\,,$$

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* Page 66.

and since the armature and external currents of this type of generator are equal, we plot the values of I_aR for various values of I_a, obtaining the straight line OB in the figure. Adding to each ordinate of the external characteristic curve, the corresponding value of the I_aR drop thus found, we obtain the total or internal characteristic as shown.

The effect of residual magnetism upon the external and total characteristic curves of a series-wound generator causes the curve to intersect the axis of volts above the origin, as indicated in Fig. 158; that is, at zero external current, and hence zero field-exciting current, an e. m. f. is generated in the armature of small value, as already explained. Thus a series generator is self-starting.

Relation between Magnetization Curve and Total Characteristic Curve of a Series-Wound Generator. If it were not for the demagnetizing action of the armature current on the field, the total characteristic curve of a series-wound generator would be almost identical with the magnetization curve. The effect of the armature current is, however, either to reduce inducing flux and therefore the generated voltage which corresponds to a given field-exciting current, or to necessitate an increased field-exciting current to give the requisite terminal voltage.

Dependence of the Characteristic Curve on Speed. Since the flux has a definite value for a given value of current output of a series-wound generator, and therefore independent of the speed, the generated voltage is proportional to the speed for a given value of the output current. The external characteristic curve corresponding to the speed n' may in consequence be derived from the external characteristic curve corresponding to the speed n, as follows: Add IR to each ordinate of the given characteristic, thus finding the total characteristic for the same speed n.* Then multiply the ordinates of this characteristic curve by $n' \div n$, thus finding the total characteristic curve for the speed n'. Subtract IR from each ordinate of this curve, thus obtaining the external characteristic curve for the speed n'.

Drooping of the External Characteristic Curve. It would seem as though the useful flux entering the armature teeth of a series-wound generator should increase more and more with the current output of the machine. As a matter of fact, the effect of magnetic leakage around the armature caused by the reactions of the armature current, is to cause this useful flux actually to decrease in value when the current output is excessive, especially if the iron in the field-circuit becomes saturated before that in the armature circuit. This decrease in the useful flux entering the armature means an actual decrease in the generated e. m. f.; and of course the terminal voltage falls off, though more than that generated on account of I_aR drop, as shown in Figs. 157, 158, and 159.

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* n = Initial speed; n' = Final speed.

Fig. 159 shows the external characteristic curve (full line), and total characteristic curve (dotted line), of a Wood arc-light, series-wound generator, with its governing device for maintaining a current of nine amperes disconnected (as indicated by the broken line *pI*).

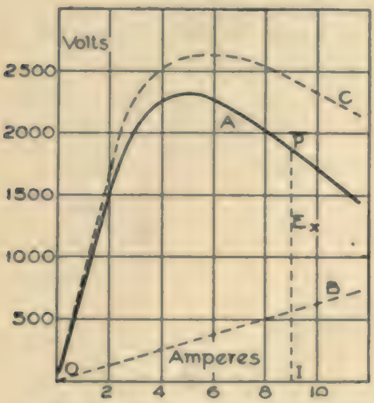

Fig. 159. External (Full-Line) and Total (Dotted) Characteristic Curves of a Wood Arc-Lighting Series Generator with Governing Device Disconnected.

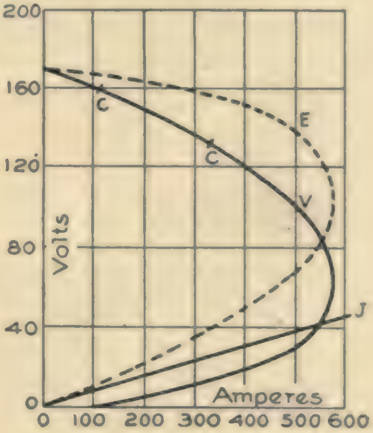

Fig. 160. Characteristics of a Shunt Dynamo.

Characteristic Curves of Shunt-Wound Generators. The external characteristic curve of the shunt-wound generator is determined experimentally by running the machine at rated speed and noting the terminal voltage for various values of the external current.

External and Total Characteristic Curves. The full line in Fig. 160 represents the external characteristic curve of a typical shunt-wound generator, the portion *cc* being that part upon which machines of this type are usually operated.

The total or internal characteristic curve is shown by the broken line in the same figure, and is calculated from the external characteristic curve as follows: Consider a point upon the external characteristic curve. The corresponding point upon the total characteristic curve is found by increasing the abscissa by the value of the shunt current so as to obtain the armature current, and by adding to the ordinate the voltage-drop in the armature and brush contacts to get the generated e. m. f.

These are seen to differ radically from the corresponding curves of the series-wound machine. The figure shows that the curves begin at a point where the terminal and generated volts are maximum, and descend slightly at first and then rapidly, finally returning in the direction of the origin, but cutting the axis of abscissæ before reaching it. The straight portion of the curve, after the bend, represents the unstable state when the shunt current is less than its true critical value. The slope of the line which constitutes the latter portion of this characteristic, represents for this particular speed, that external resistance below which the magnets lose their magnetism at once.

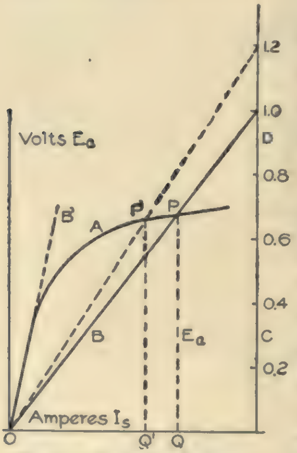

Fig. 161. Relation between Voltage and Speed in Shunt Generator.

The effect of residual magnetism upon the external characteristic curve of a shunt-wound machine is to cause it to intersect the ampere-axis to the right of the origin, as indicated in Fig. 160.

Voltage-Speed Characteristic Curve of Shunt Generator at No-Load. The relation between the speed of a shunt generator and its voltage is much more complicated than in the case of the separately excited or series-wound machines, since a higher speed increases the generated e. m. f. It thus causes a greater exciting current to flow in the field-windings, resulting in a still higher value of machine voltage until practical saturation is reached. We may construct the curve showing this relation from the magnetization curve of the machine, as follows: Let OA, Fig. 161, be the magnetization curve of a shunt-wound machine at a speed n. Draw the straight line OB, of which the abscissæ represent values of the shunt field-exciting current I_{sh}, and the ordinates represent values of the voltage $r_{sh} I_{sh}$ required to produce the corresponding values of I_{sh}. The co-ordinates of the point of intersection of OA

and OB will then represent the values of E, which is practically equal to V at no load, and to I_{sh} when the machine is driven at speed n.

Draw the line CD perpendicular to the axis of abscissæ, and draw the line OP through P until it intersects this vertical line, making $PQ = E$. The point of intersection of OP and CD then represents the value of r_{sh} at the speed n. Now lay off on CD a scale of values of r_{sh}, taking the actual value of r_{sh} at speed n as unity.

Now suppose it is required to find the value of E for a speed $n' = n \div 1.2$. As a first step, imagine that the value of r_{sh} is increased from unity to 1.2, the speed meanwhile remaining constant. Under these conditions, we have $E' = Q'P'$. Now imagine this increased value of r_{sh}, and the original speed n, to be both decreased in the ratio 1.2:1. This would bring r_{sh} back to its original value, and would reduce the value of E' (*i.e.* $Q'P'$) in the ratio 1.2:1. Therefore the required value of the generated e. m. f. at speed n' is $(1 \div 1.2)\,Q'P'$.

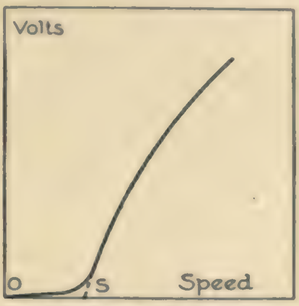

Fig. 162. Typical Voltage-Speed Characteristic of a Shunt Generator at Zero Current Output.

Fig. 162 shows a typical voltage-speed characteristic curve of a shunt generator at zero load. If it were not for the effect of residual magnetism, this curve would cut the speed axis at S. The speed corresponding to S is called the *critical speed* of the given shunt-wound generator; and when the speed is less than this value, it cannot build up at all.

The critical speed may be obtained from Fig. 161 by extending the line tangent to OA at O (*i.e.*, OB'), until it intersects CD produced, at a point which is equal to $n \div n''$; whence n'' is the critical speed.

Relation between Magnetization Curve and Total Characteristic Curve of a Shunt-Wound Generator. Let us assume OA as the magnetization curve of the machine in Fig. 163, the ordinates of the straight line OB representing the values of $V = r_{sh}\,I_{sh}$. Consider any given point P on OB. The abscissa OS is the shunt field-exciting current I_{sh}, and the ordinate SP is V. It remains to find the point P' on the total characteristic curve corresponding to P.

Let n be the number of turns of wire in the shunt field-winding, and let d be the number of demagnetizing turns on the armature, through each of which the entire armature current may be considered as flowing. Then the resultant field-excitation is $(nI_{sh} - dI_a)$[*] ampere-turns, which may be written $n\,(I_{sh} - I_a d \div n)$. It follows, then, that the actual resultant field-excitation and the actual value of E are such as would be produced by a field-exciting current equal to $I_{sh} - I_a d \div n$ acting alone; that is, the distance $Q\,P''$ is equal to $I_a d \div n$, P'' being the unknown point on the magnetization curve corresponding to P Furthermore, the ordinate of P'' is, of course, E, so that the distance QP is equal to $E - V = r_a I_a$. Now, as I_a is as yet unknown, but since we have $PQ = r_a\, I_a$, and $QP'' = I_a d \div n$, it is evident that the direction of PP'' is independent of I_a. In fact, the direction of PP'' may be once for all determined by laying off $PM = r_a I_a$ and $MN = I_a d \div n$ for any arbitrary value of I_a. The line PN then fixes the direction of PP'', and the point P'' is found at the intersection of PN and OA, as indicated.

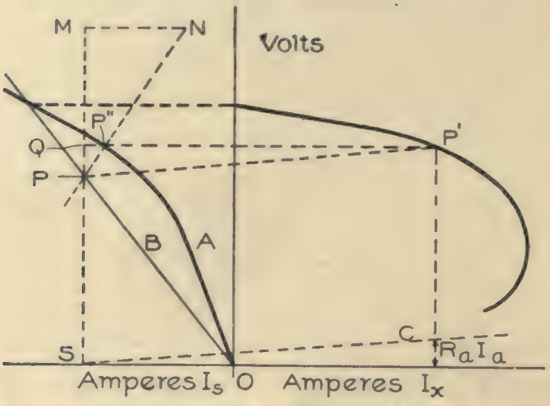

Fig. 163. Relation between Magnetization Curve of a Shunt Dynamo and Its Total Characteristic as a Generator.

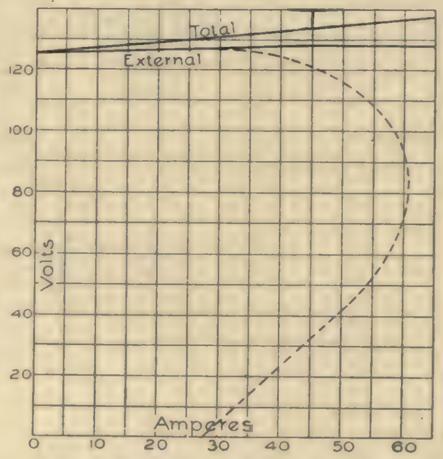

Fig. 164. Total and External Characteristic Curves of Compound-Wound Generator.

Having thus determined the point P'', the point P' on the total characteristic curve which corresponds to the chosen point P, lies on a horizontal line drawn through P'', and the abscissa of P' is determined by the condition that the corresponding ordinate of SC' shall be equal to PQ ($= r_a I_a$). The point P' thus determined is most easily located by drawing a line through P parallel to SC. Such a line will intersect the horizontal line through P'' at the desired point P'.

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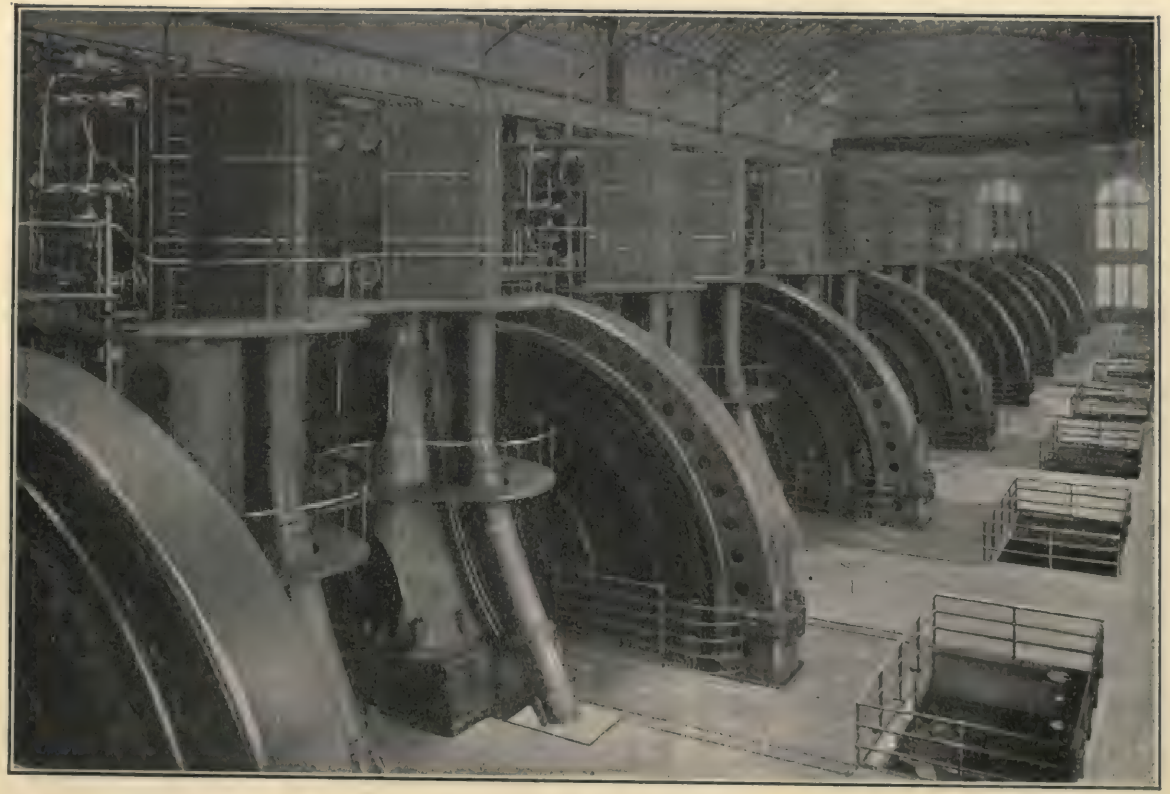
[*] The value of d is equal to $\frac{2\alpha}{360°} \times \frac{Z}{c}$, where α is the angle of brush lead.

Characteristic Curves of Compound-Wound Generators. The compound-wound generator has heretofore been treated as a shunt dynamo to which series turns have been added to compensate for the internal drop, and to raise the terminal voltage with load if desired. Consequently there is no need now to discuss this type of generator minutely.

Fig. 164 shows the external and total characteristic curves of a typical over-compound-wound generator, the terminal voltage of which rises with increase of current up to and beyond rated load. The dotted portion of the curve shows the rapid fall of terminal voltage as the load is still further increased, resulting from the great demagnetizing action of the current in the armature and from the decrease of that part of the field-excitation which is due to the shunt field-exciting current.

The computation of the number of series turns has been previously given, so that nothing further remains to be considered.



EIGHT 5,000-K. W. GENERATORS, INSTALLED AT THE MANHATTAN STATION, NEW YORK CITY

Westinghouse Electric & Mfg. Co.

DYNAMO-ELECTRIC MACHINERY

PART III

DESIGN OF DIRECT-CURRENT DYNAMOS

In considering the various parts of continuous-current generators from a constructive point of view, we shall group the details under the following heads:

(1) Construction of the Frame.
(2) Construction of the Armature.
(3) Commutator and Brush Construction.
(4) Construction of the Mechanical Parts.

CONSTRUCTION OF THE FRAME

The frame of continuous-current machines is usually composed of the *magnet-yoke* or *ring*, the *field-poles* and their projections, and the *field-winding*.

Magnet-Yoke. We have seen that the ring type of magnet-frame is now generally used. It is made either of cast iron or cast steel in continuous-current machines, and in section takes one of the shapes of Fig. 165, the poles projecting inwardly. *A*, *B*, and *C* are suited to cast-iron; while *D*, *E*, and *F* are of cast-steel construction. The first two are simple types which need no explanation. *C* is employed by the Crocker-Wheeler Company, the flange on either side serving to stiffen the ring and to protect the field coils. *D* is used by the Oerlikon Company, and *E* by the General Electric Company, both designed to secure stiffness.

The choice between cast steel and cast iron for the yoke, depends upon the purpose for which the machine is intended and the ideas of the designer. The advocates of cast iron claim that by its use the machine is made heavier in the stationary part, and thus better enabled to withstand any tendency to vibrate. The other side claim that great weight is unnecessary.

The magnet-ring in all but the smallest machines is split in two along its horizontal diameter, or sometimes along its vertical diameter, to facilitate erection, inspection, and repair with respect to the armature. The two parts are usually held together by bolts at the side, back, or interior of the ring, as indicated in Fig. 166 (*a*, *b*, *c*). One or more ring-bolts are also placed at the top or on each side of the upper half in order to make handling easy.

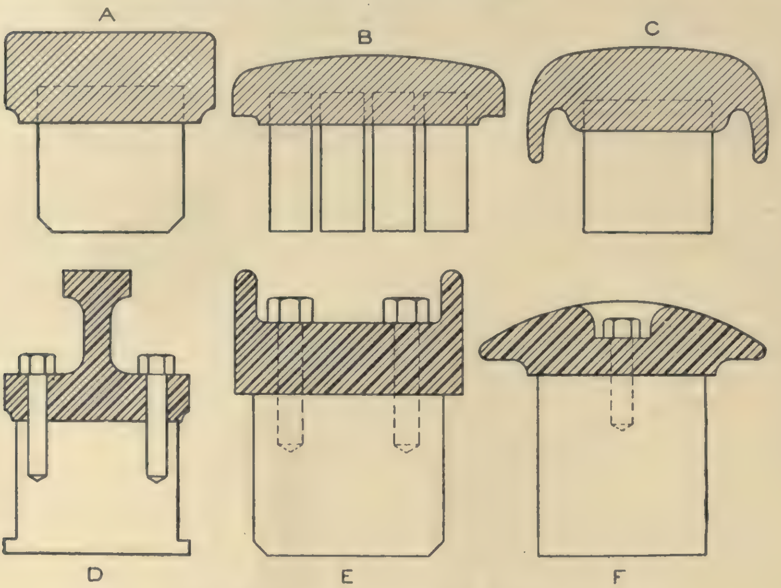


Fig. 165. Various Sections of Magnet-Yokes.

Field-Poles and Projections. The field-poles are generally made of wrought iron, sheet steel, or cast steel. The magnetic properties of these materials are given in Fig. 112. Wrought iron and cast steel have approximately equal permeabilities at about 95,000 lines per square inch, below which the former is a little superior. The objection to the use of wrought iron, however, is the difficulty of making it in the forms required. This may be partly avoided by using simple forms such as a plain cylinder, which can easily be made by forging or by cutting off lengths from round bars.

The cheapening and developing of the process of casting "mild" steel (soft steel), with a very small amount of carbon, has resulted in the general adoption of this material for field-magnets. It combines high permeability, cheapness, strength, and the ability to be cast in any reasonable form. It is certainly not economical to use cast iron for the cores of the field-magnets, since it requires from 2 to 2.5 times the cross-section of wrought iron or steel for the same reluctance. With a circular cross-section, this demands about 1.5 times the length

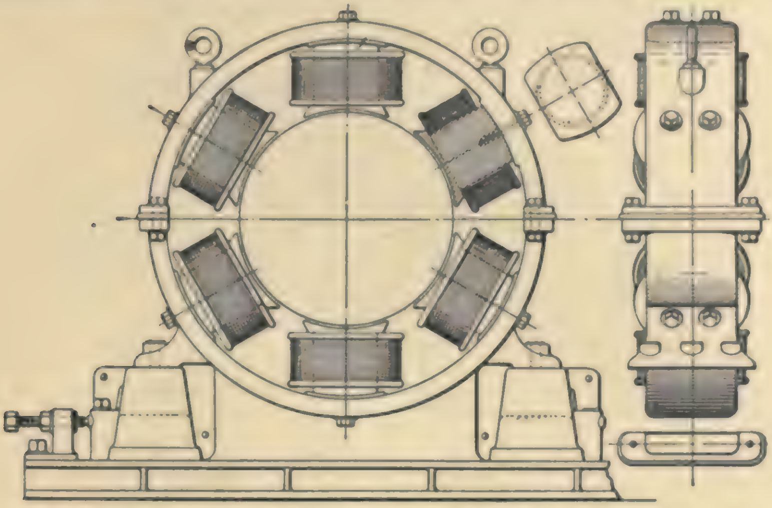


Fig. 166a. Magnet-Yoke with Parts Bolted Together at Back and Front of Ring.

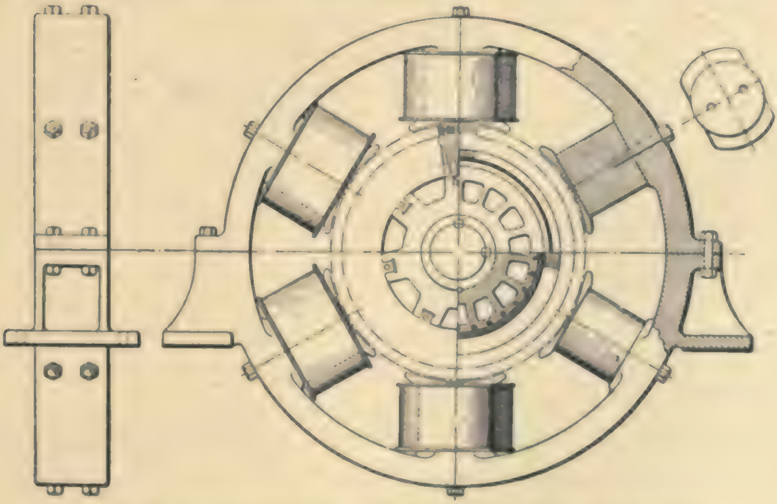


Fig. 166b. Magnet-Yoke with Parts Bolted Together at Sides of Ring.

of wire for a given number of ampere-turns; and the necessary weight of cast iron being 2 or 2.5 times greater, makes it not only clumsy but more expensive. For pole-pieces, yokes, field-rings, bases, or other parts not wound with wire, the extra circumference is not so objectionable. Often the increased weight is positively advantageous in giving greater stability, so that cast iron is still used to some extent in these parts.

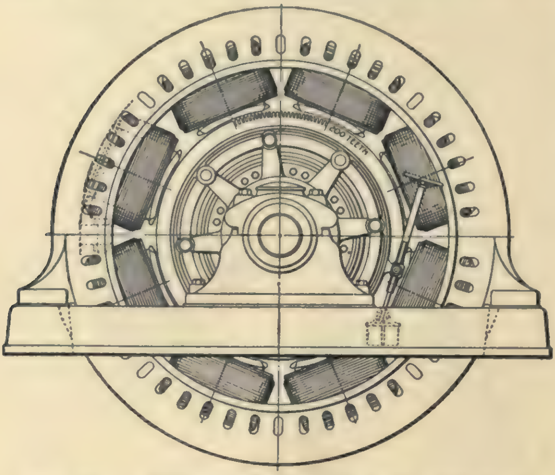
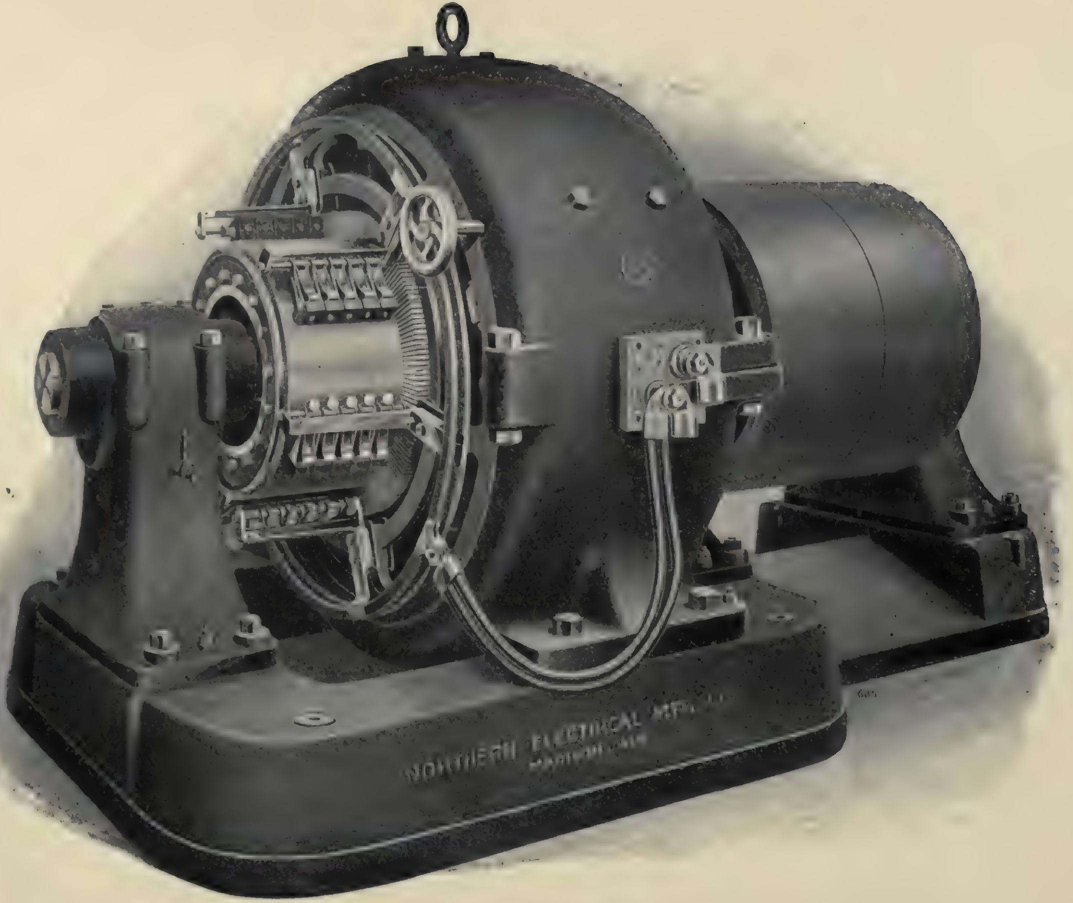


Fig. 166c. Magnet-Yoke with Parts Bolted Together on Inside of Ring.

In joining cast iron to wrought iron or steel, it is hardly sufficient to butt the two together, as indicated in Fig. 103, because the permeability of a given area of cast iron is only about one-half as great as that of an equal area of either of these other materials. Hence, in order to secure the proper surface of contact, the pieces of steel or wrought iron should be imbedded in the cast iron by placing the former in the mould when the casting is made, or the cast iron may be bored out to receive the ends of the cores. Joints in the magnetic circuit are not desirable, because they involve work in fitting, and may cause looseness or weakness—usually avoidable, however, with good workmanship. On the other hand, the common idea that they introduce great reluctance is not true, for we have seen on page 12, that an ordinary joint is equivalent to an air-gap of about 0.002 inch, which is practically insignificant, and does not warrant the making of complicated castings or forgings to avoid one or two joints in the magnetic circuit, except to simplify mechanical construction.

The length of the cores required for a given field-magnet depends simply upon the amount of field-winding. The turns needed are computed as described on pages 77-86, and the size of wire from pages 86-7. It is sufficient to make the core long enough to



BELTED GENERATOR.

Ring Type, Three Bearing, Six Pole.

receive these turns properly, and expose sufficient surface to dissipate the heat generated by the field-current, to prevent excessive temperature-rise, as indicated on page 91.

The area of cross-section of the field-cores is determined by the total flux to be carried. A density of 13,000 to 16,000 lines per square centimeter (80,000 to 100,000 lines per square inch) is about the value for cast steel or wrought iron. The section is either rectangular or circular, the latter being preferable on account of ease of winding coils for this shape, and because a circle has the least circumference for a given area, thus requiring less wire. The rectangular shape is used where the pole-core is laminated; and with the same area as one of circular cross-section, it has more radiating surface, although more wire is required for each turn.

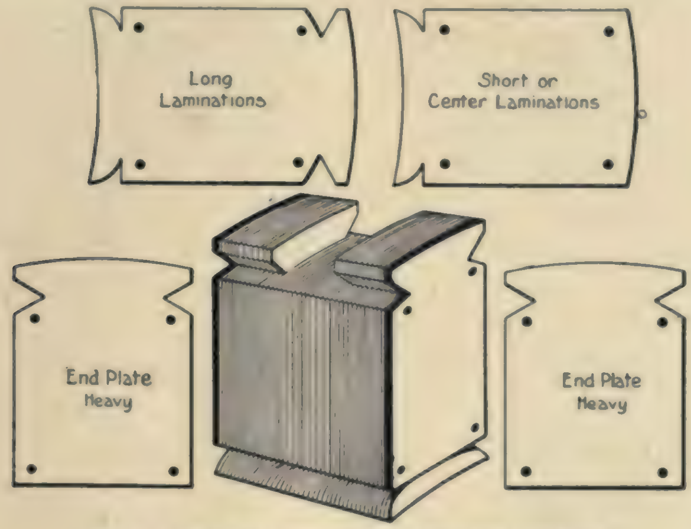


Fig. 167. Pole-Core Stampings and Assembled Pole-Piece.

The field-cores are attached to the yoke in several ways. The simplest method is to cast them as one piece or to bolt them together as indicated in *D*, *E* and *F* of Fig. 165. Another method is to place the cores of cast steel in the mould when casting the ring of cast iron. Sometimes, for large machines, only a portion of the cores is cast with the yoke, the rest being attached to the pole-pieces or shoes after mounting the field-coils. The two portions are then held together by bolts passing through the pole-shoe.

Most continuous-current machines are designed with an extended pole-piece or shoe which covers a greater surface than would the mere end of the field-core. Great attention has been paid to the special shaping of these polar extensions, as noted on page 54, and in most cases they are constructed separately and attached to the cores while assembling the machine. If the core is laminated, the pole-piece forms a part of the laminæ, as shown in Fig. 167; while, if the core is partly cast with the ring, and the remainder bolted to it, as stated above, the shoe forms a portion of this addition.

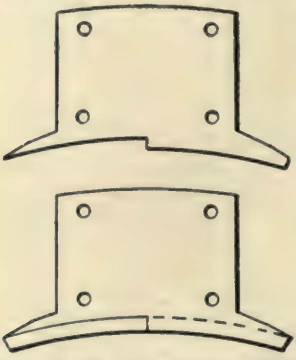


Fig. 168. Shaped Pole-Stampings.

An extended pole-piece reduces the reluctance of the air-gap, and the ampere-turns needed in the field-winding. On the other hand it is well to have the pole-shoe itself well saturated. Hence, to fulfil both conditions, either it ought to be made of a less permeable material than the pole-core (if the latter is cast steel or wrought iron, the pole-shoe may be of cast iron), or, if made of stampings of wrought iron or mild steel, it should be so designed that its edges at least will be well saturated. This can be accomplished as indicated in Fig. 168—that is, by omitting every other lamina in the pole-piece.

Field-Winding. Coils for field-magnets may be classified as (*a*) *bobbin-wound*, and (*b*) *form-wound*. With respect to those wound on bobbins, no special instructions need be given, except for fixing and bringing out the ends, the insulation, etc. Rectangular conductors, while preferable where the cross-section of the wire is large and the radial depth of winding is considerable, cannot always be used, because special facilities are involved. Where edge-strip winding is possible, its use is generally advisable.

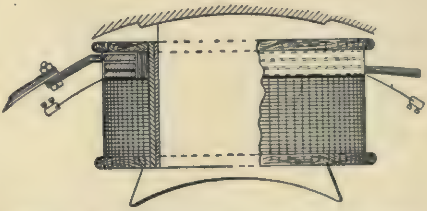


Fig. 169. Field-Magnet of Scott & Mountain's Six-Pole Generator.

Field-Magnet Bobbins. These are made variously of brass with brass flanges, of sheet iron with brass flanges, of very thin cast iron, or sometimes of vulcanized fiber. Some makers use sheet metal with a flange of some hardwood, such as teak, examples of which, as well as of other common designs, are shown in Figs. 169, 170, 171, and 172. Care must be taken to line the bobbins with adequate insulating materials, such as layers of oiled silk or muslin, vulcanized fibre, or varnished mill-board. Great attention must also be paid to the manner of bringing out and securing the inner end of the coil. If a bobbin is simply put upon a lathe to be wound, the inner end of the wire, which must be properly secured, requires to be brought out in such a way that it cannot possibly make a short-circuit with any of the upper layers, as it crosses them. A method of winding which obviates this difficulty is to wind the coil in two separate halves, the inner ends of which are united, so that both terminals of the coil come to the outside. Fig. 173 shows such a bobbin, this method having also been used in the manufacture of induction-coil secondaries, for which it is desirable to keep the ends away from the iron core and from the primary coil.

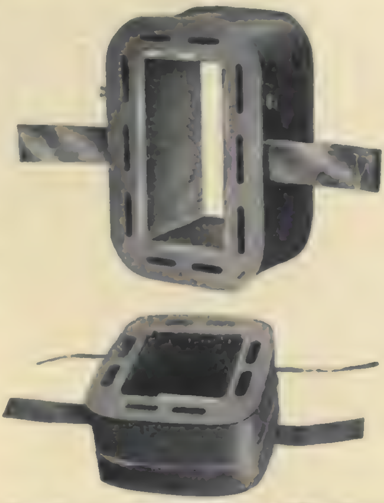


Fig. 170. Rectangular Types of Ventilated Field-Coils.

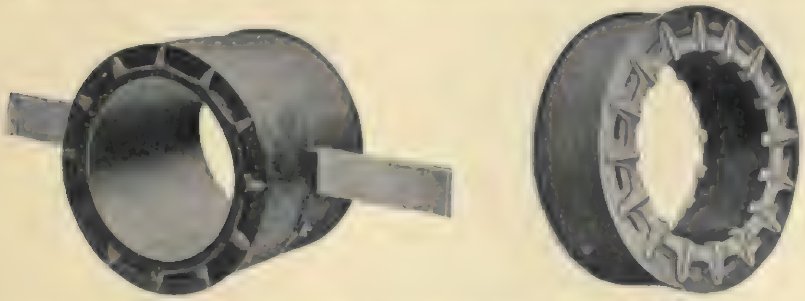


Fig. 171.

Fig. 172.

Circular Types of Ventilated Field-Coils.

Again, the winding may be piled up conically, as in Fig. 174, without any end-flanges, thus avoiding some of the risks of breakdown, and bringing both free ends to the outside. In winding copper strip for some continuous-current machines, a similar plan has been adopted, the union of the two strips being effected at the interior of the coil, as indicated in Fig. 175. In still another type of continuous-current generator, the field-cores, which are removable, are themselves shaped to serve as bobbins, and, after being covered with a protecting layer of insulating material, are wound in a lathe, as illustrated in Fig. 176.

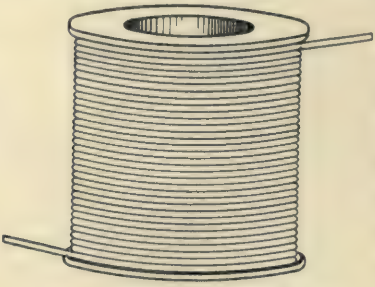


Fig. 173. Bobbin with Both Ends at Outside.

Form-wound coils are made upon a block of wood or a brass frame, to which temporary flanges are secured to hold the wires together during winding. Such coils have pieces of strong tape wound in between the layers and lapped at intervals so as to bind them together. The completed coil is then served with two or more layers of tape, each separately soaked in insulating varnish. The whole coil is soaked in an insulating varnish and then baked in an oven, current being simultaneously sent through the wire to insure interior drying. Figs. 177, 178, and 179 illustrate form-wound coils; while Figs. 171, 172, and 180 represent bobbin-wound types.

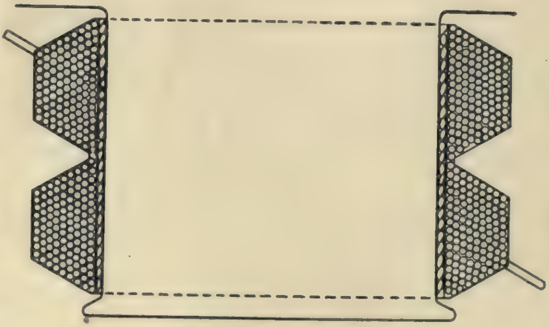


Fig. 174. Brown's Piled High-Voltage Coil.

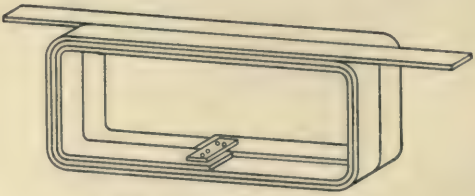


Fig. 175. Strip-Wound Coil.

Bringing Out and Fixing Ends. Figs. 181 and 182 illustrate common means for bringing out the ends of coils. In Fig. 181, copper strip, laid behind an end-sheet of insulating material, makes connection to the inner end, as shown in the upper part of the figure; while another strip, shown similarly inlaid in the under part, serves as a mechanical as well as electrical attachment for the outer end of the winding. Another method, shown in Fig. 182, also greatly reduces the danger of breaking the connection to the interior of the coil. Fig. 183 illustrates a simple device for securing the outer end by means of a terminal piece laid upon the coil, the last three or four turns of which are bared and wound over it, a permanent joint being obtained by soldering.

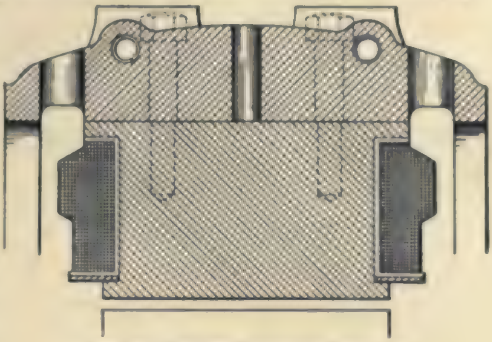


Fig. 176. Wound Pole-Core (Alioth).

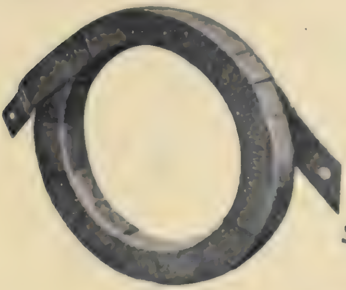


Fig. 177.

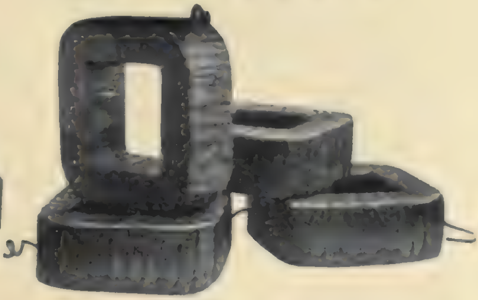


Fig. 178.

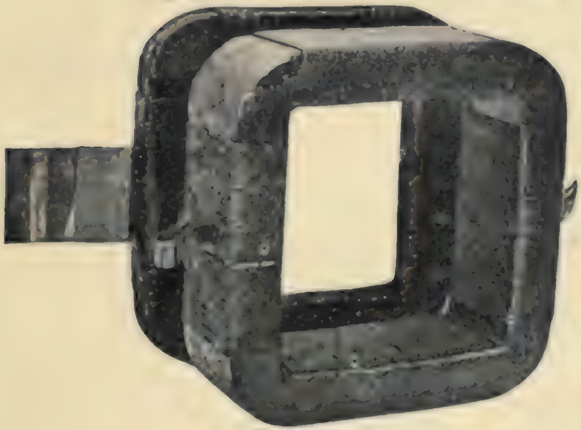


Fig. 179.
Types of Form-Wound Coils.

Insulation of Field-Magnet Coils. It is not necessary to use any mica for the insulation of field-magnet bobbins, several thicknesses of paper preparations being more often used. One-tenth inch or more thickness, if composed of several superposed layers, is generally adequate. Varnished canvas is useful as an underlay, and press-spahn or vulcanized fibre for lining the flanges. It is also important to protect the joint between the cylindrical part of the bobbin and the end flanges.

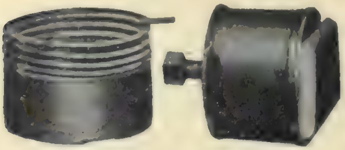


Fig. 180. Bobbin-Wound Coil.

The lagging of varnished cord with which the completed coil is usually covered, acts as a mechanical protection; but this is not altogether a benefit, since it retards the dissipation of heat.

Attachment of Magnet-Coils. The ordinary mode of supporting the field-coils is by means of the pole-shoe, which is usually removable from the core. If not so arranged, the core and shoe together are made removable. Some machines are not provided with pole-shoes, in which cases other means must be supplied to support the magnet-coils. One method consists in screwing side brackets to the end of the core. Another way, illustrated in Fig. 184, is to provide triangular blocks of hardwood, which lie in the space between the tips of two adjacent poles and are secured to the ring by bolts. Fig. 185 shows still another scheme for anchoring the field-coils.

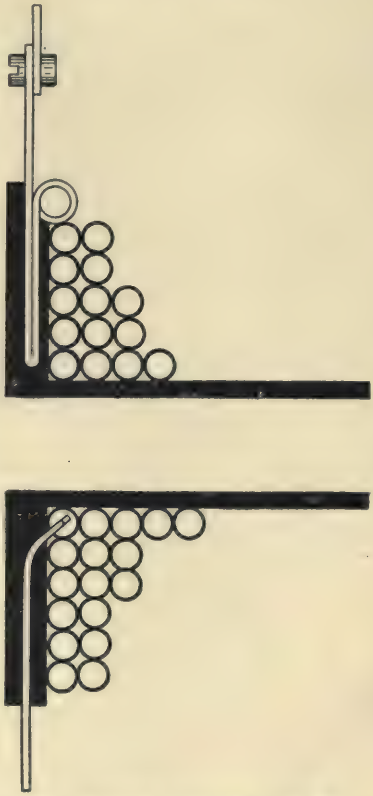


Fig. 181. Mode of Bringing Out Ends of Coils.

CONSTRUCTION OF THE ARMATURE

Core-Bodies. The cores of armatures are universally made of laminæ—thin discs—of wrought iron or mild steel. These discs are stamped out of sheet metal, and range from 0.014 inch to 0.025 inch in thickness, the former thickness being that often used at the present time. Core-discs up to about 30 inches in diameter are punched in one piece; while larger diameters are stamped out in sections (Fig. 186), and the core built up as indicated in Fig. 187, alternating the joints. These stampings are now so accurately made, that, after assembling the discs into a core, the slots need not be milled out as was formerly necessary. Milling is most objectionable, because it burrs over the edges of the discs and defeats the purpose of lamination by connecting adjacent discs and facilitating the flow of eddy currents. For the same reason, turning, after assembling, also tends to increase the iron losses. Hence, if it is found that the periphery of the core-body is irregular, it should be *ground* true.

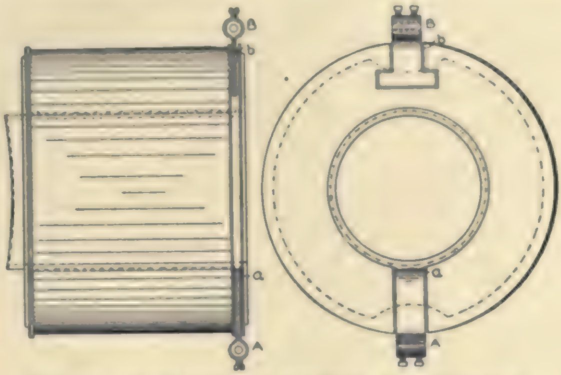


Fig. 182 Ganz's Method of Bringing Out Ends of Coils.

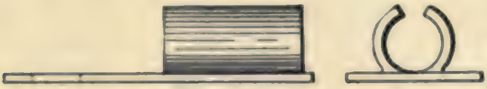


Fig. 183. Coil Terminal Piece.

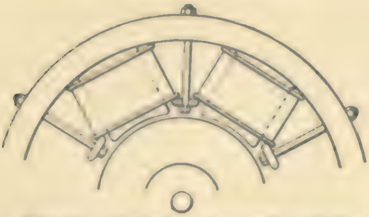


Fig. 184. Method of Anchoring Coils.

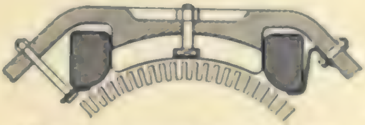


Fig. 185. Another Method of Supporting Coils.

The core-discs are insulated from each other either by a thin coating of iron oxide on the discs, a thin coating of water-glass enamel applied to the sides of the discs by a machine, or a thin coating of japan varnish similarly applied. Sometimes shellac or paper is used for insulating these laminæ; but on account of the greater expense and the fact that the efficiency is only slightly bettered, the latter are applied only in special cases.

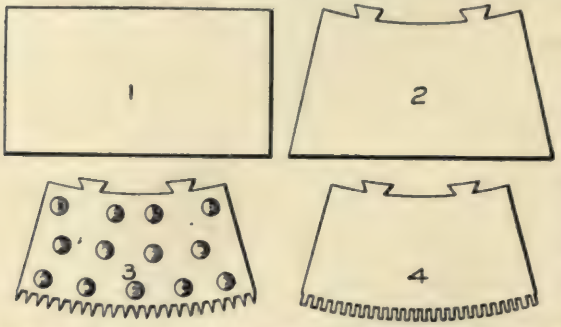


Fig. 186. Core-Segments and Ventilating Segments, Stamped.

Shapes of Armature Teeth. A common form of armature tooth is that depicted in Fig. 188, being slightly narrower at the root than at the top, the resulting slot having parallel sides. Fig. 189 illustrates a form in which the tops are slightly extended to give a larger magnetic area at the top, thus decreasing the reluctance of the air-gap, and helping to retain the conductors in the slots by the insertion of a wedge of wood. The latter object is attained by notching the teeth as in Fig. 190, in case it is not desirable to increase the area of the top of the tooth.

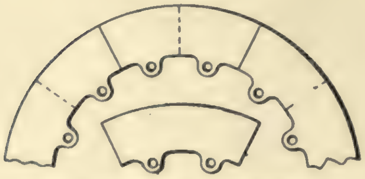


Fig. 187. Core Built of Segments.

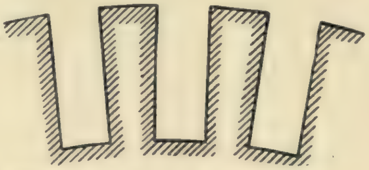


Fig. 188. Teeth with Parallel Slots.

End Core-Plates. It is usual to place at the ends of the core, plates of sheet iron of a greater thickness than the laminæ, so as to support and protect the latter. They are usually 0.125 inch thick, and sometimes ribbed to give added stiffness.

Binding-Wire Channels. In machines using binding wires to hold the armature conductors in the slots, it is usual to stamp some of the core-discs of slightly reduced diameter so that the binding wires may be flush with the surface of the armature. The reduction is seldom more than ¼ inch on the diameter, giving a channel not over ⅛ inch deep. The width is determined by the number and size of the binding wires (see page 131).

Mounting of Core-Discs. Some mechanical means must be provided to hold the core-discs together, and to connect them rigidly to the shaft. The methods may be broadly divided into two classes, depending on whether the discs are keyed directly to the shaft, or to some auxiliary support attached to the shaft.

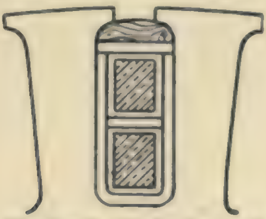


Fig. 189. Teeth with Projecting Tops.

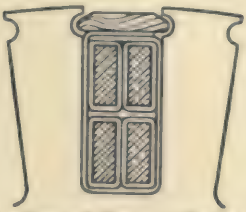


Fig. 190. Notched Teeth, to Hold a Wedge.

In the case of small cores not exceeding 15 inches in diameter, the core-discs take either of the forms shown in Figs. 191 and 192, the latter being preferable on account of increased ventilation. These laminæ are simply keyed to the shaft, being held together under heavy pressure by end-plates of cast steel or cast iron, which are in turn pressed inward either by nuts fitting in threads upon the shaft, or by bolts passing through but insulated from the armature discs and end-plates.

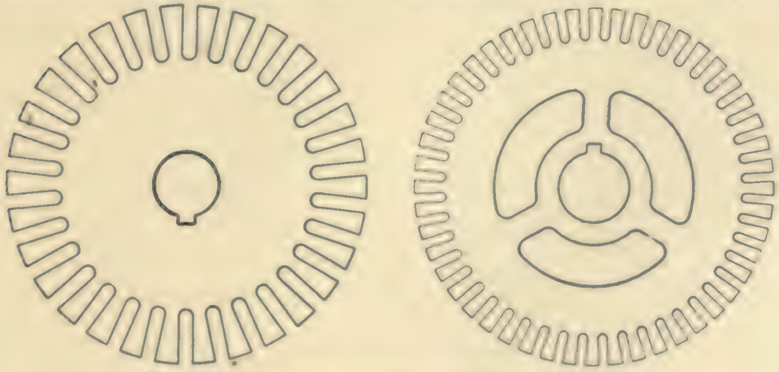


Fig. 191. Fig. 192.

Forms of Armature Core-Discs.

Large cores in which the discs are made in sections, or for which the material of the core near the shaft is not required, are built upon an auxiliary support called a *spider*, which has different forms, depending on the mode of attachment between it and the core-discs. Fig. 193 shows the discs held together and to a skeleton pulley, or spider, by bolts passing through them, the spider being keyed to the shaft. The objection to this construction is the fact that the bolt-holes reduce the effective area of the core, thus strangling the magnetic flux. This may be overcome by placing the bolts internal to the core, as in Fig. 194, in which case they need not be so well insulated. Another arrangement which is more modern, is to provide the discs with dovetail notches or extensions, fitting into extensions or notches

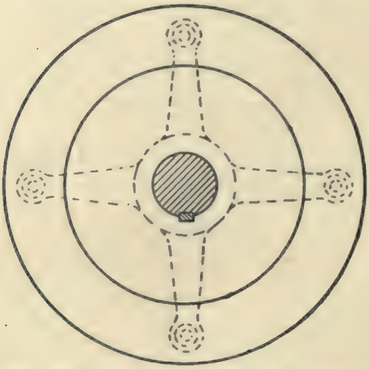


Fig. 193. Core-Discs Bolted to Spider.

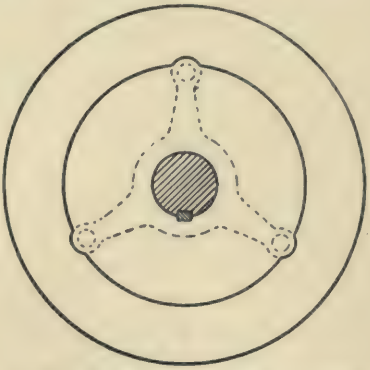


Fig. 194. Bolts Placed Internal to Core.

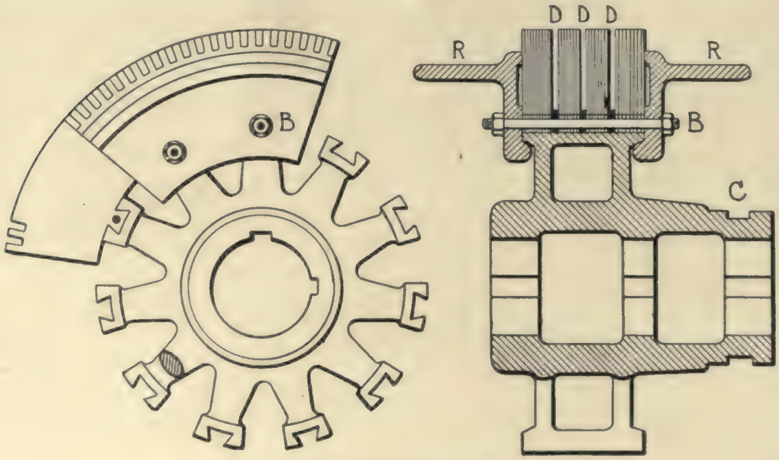


Fig. 195. Mounting of Large Armature Core.

on the spider arms, as in Fig. 195. The sectional view shows the method of holding the laminæ together by means of bolts and end-plates, also the extension (*R R*) for supporting the end-connections of a barrel-winding.

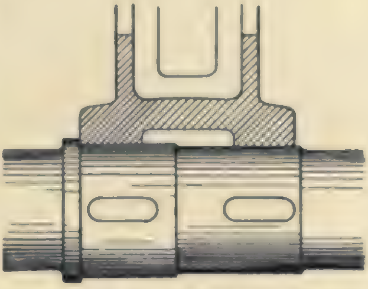


Fig. 196. Construction of Armature Hub.

The hubs of armature spiders, in order to facilitate fitting the shaft, are usually cleared out between their front and back bearing surfaces; and in larger sizes, the seating on the shaft is often turned to two different sizes to admit of easier erecting, as in Fig. 196.

Figs. 197 and 198 show a spider and other features of construction of a large machine. The rim is cut into six pieces, each of which has four dovetail notches. If cast in one piece, trouble might arise from unequal strains in the metal, due to contraction. Ventilating

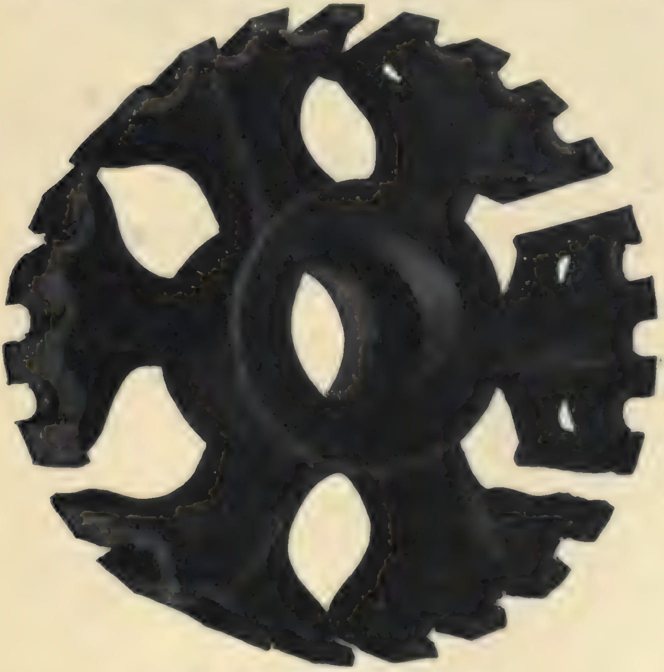


Fig. 197. Spider for Bullock Armature.

apertures are provided, and on the side of each arm (Fig. 197) are seen the seatings and bolt-holes for attaching the commutator-hub and the rim which supports the winding. In Fig. 198, which depicts the completed core, are visible the supporting rim and narrow ventilating ducts.

Ventilating Ducts. Armature cores, as already explained, heat from three causes—namely, hysteresis and eddy currents in the iron, and I^2R losses in the copper conductors. In order that the temperature-rise of the armature shall not exceed a safe figure, 50°C., it has been found necessary, in the large and heavy-duty types of to-day, to resort to positive means of ventilation, usually consisting of ducts which lead the air between the core-discs. To keep the core-discs apart at these ducts, it is necessary to introduce distance pieces, or *ventilators*, Fig. 199 illustrating some of these devices.

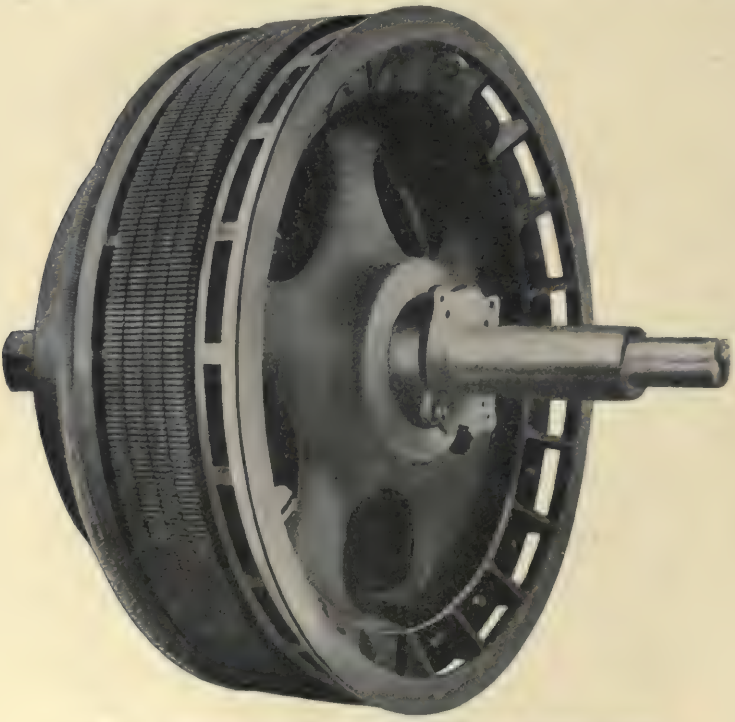


Fig. 198. Armature Core and Commutator with Temporary Shaft.

In *a*, simple pieces of brass are riveted radially at intervals to a special core-disc 0.04 to 0.05 inch thick. This form fails to provide adequate support for the teeth, which is obviated in *c*, where behind each tooth there is a strip of brass about 0.4 inch wide set edgewise, being cast with or brazed to a special casting of brass riveted to a stout core-disc. In a recent construction shown in Fig. 200, the core-plate next to the duct is ribbed, affording good support for both the core and teeth of the next plate. Fig. 186, on page 166, illustrates a somewhat similar device.

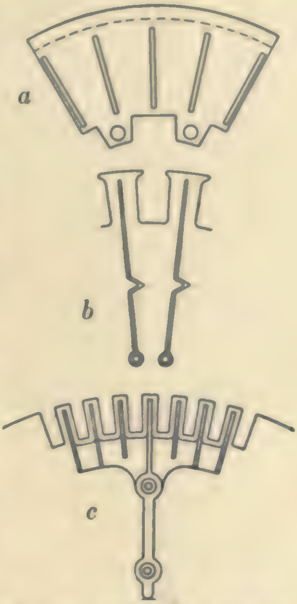


Fig. 199. Ventilating Devices.

Binding Wires. With toothed-core armatures the conductors may be held in the slots by wedges of wood, as already mentioned, or by bands of wire wound around the armature. These binding wires must be strong enough to resist the centrifugal force tending to throw the armature conductors out of the slots, and yet must occupy as little radial space as possible, in order not to interfere with the clearance between the armature and the pole-pieces. The common practice is to employ a tinned wire of hard-drawn brass, phosphor bronze, or steel, which, after winding, can be sweated together by solder into one continuous band.

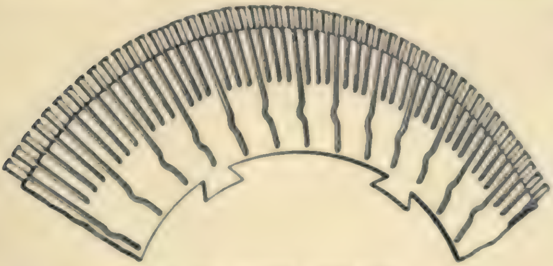


Fig. 200. Ribbed Core-Plate.

Under each belt of binding wire a band of insulation is laid, usually consisting of two layers—first a thin strip of vulcanized fibre or of hard red varnished paper, slightly wider than the belt of wire, and then a strip of mica, in short pieces, of about equal width. Sometimes a small strap of thin brass is laid under each belt of binding wire, having tags which can be turned over and soldered down to prevent the ends of the binding wires from flying out.

Wedges. In the cases where wedges are driven into grooves in the teeth, to close up the slot, the usual material employed is a well-baked hardwood, such as hornbeam or hard white vulcanized fibre. A modern method consists in using a springy strip of German silver, or a strip of *magnalium* metal.

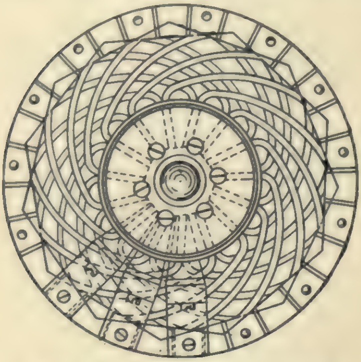


Fig. 201. Siemens Bar Armature.

Conductors. Copper is always used for the armature conductors of continuous-current machinery, either as wire strip or stranded. Wire is usually employed for machines of small or moderate current output; but rectangular conductors are preferable, especially for heavier currents, on account of better space-factor. Large, solid conductors, whether round or rectangular, are objectionable, not only on account of stiffness, but also because eddy currents may be generated in them. This is avoided by subdividing the former into several round wires or by laminating the latter.

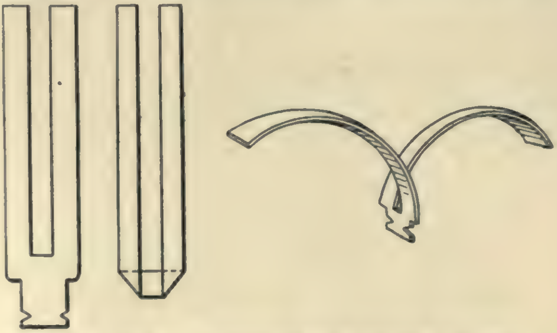


Fig. 202. Spiral End-Connectors for Evolute Windings.

Armature Windings. The different methods of armature windings have been treated at length on pages 93–120. It remains to consider the mechanical arrangements or means employed to carry out the scheme of winding adopted.

Drum Windings. Drum windings may be subdivided into (1) *hand windings;* (2) *evolute windings;* (3) *barrel windings;* (4) *bastard drum windings;* and (5) *form windings,* according to the manner in which the end-connections are made. It is essential that these latter be good conductors, sufficiently well insulated from one another, allowing of repairs and ventilation, and mechanically sound.

Hand windings, historically the first, are now seldom used, except for special machines. They involve a clumsy overlapping of wires at the ends of the armature, which stops ventilation and hinders repairs; while the outer layers, overlying those first wound, bring into close proximity conductors of widely different voltage.

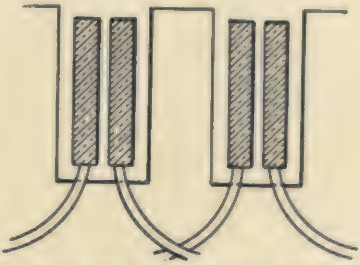


Fig. 203. Evolute Conductors in Slots.

Evolute windings, so named from the method of uniting the conductors by means of spiral end-connectors, were quite early devised to overcome the objections to the hand windings. In Fig. 201, which illustrates this construction, each inductor in the form of a bar is connected to the next by means of two evolute spiral copper strips, one bending inwardly, the other outwardly, their junction being in some cases secured to a block of wood upon the shaft. Their outer ends are attached to the bars by rivets or silver solder.

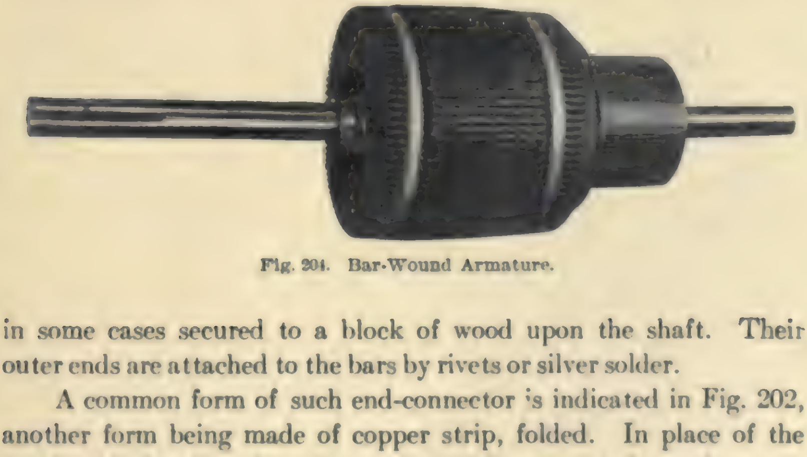


Fig. 204. Bar-Wound Armature.

A common form of such end-connector is indicated in Fig. 202, another form being made of copper strip, folded. In place of the wooden block referred to above, the middle part of the evolute connector may be anchored to an insulated clamping device built up like a commutator and called from this resemblance a *false commutator*.

In evolute windings the spiral connectors lie in two planes, back of one another; hence it is necessary that the armature bars should project to different distances beyond the core-body, the shorter ones being joined to the inner layer of evolutes, the longer ones to the outer layer. For this purpose it is convenient to arrange one short and one long bar in a slot, side by side, as in Fig. 203 or in the finished armature of Fig. 204.

Barrel windings were devised by Mr. C. E. L. Brown in 1892, as an improvement upon the evolute windings just described, and are most extensively used to-day. The method consists in arranging the conductors in two layers, so that their ends, instead of being carried down as evolutes, are continued out upon an extension of the cylindrical surface of the armature and are bent to meet obliquely in two overlapping layers. This scheme, like the evolute winding, is adapted to wave as well as lap windings. Its only disadvantage lies in the fact that it requires the length of the armature parallel to the shaft to be greater than in the previous case. Its great advantage lies in the excellent ventilation made possible by the larger cooling surface, and by permitting air to enter the interior of the armature at the ends.

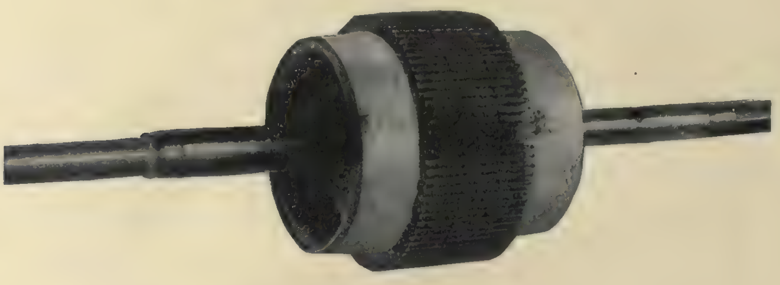


Fig. 205. Armature Body before Coils are Placed in Position.

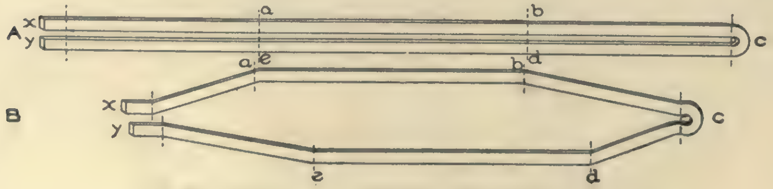
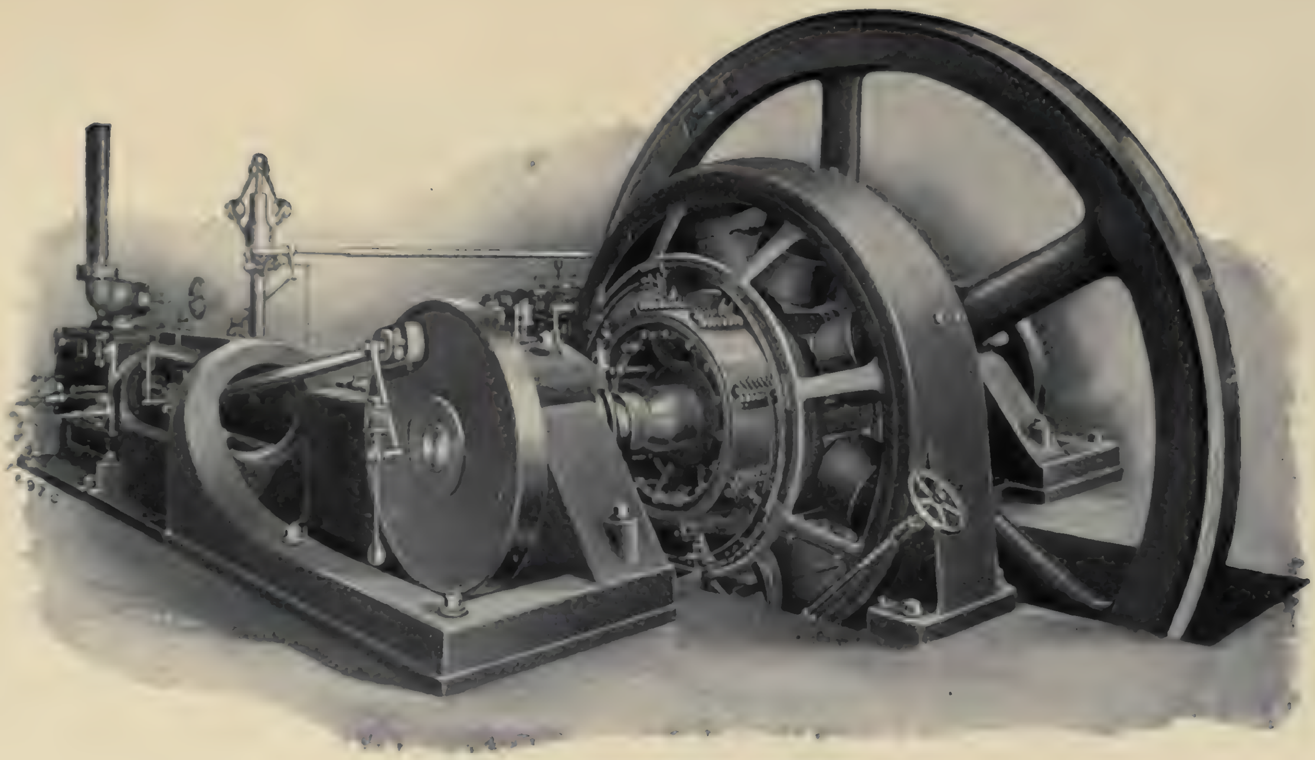


Fig. 206. Element of Lap Winding Formed from Strip.

A usual method of supporting the extended end-connections



"NATIONAL" ENGINE-TYPE GENERATOR.

200 K.W. 250 Volt, 125 R.P.M.

is to attach to the end of the armature body ventilated brackets, as indicated in Fig. 205. A simple way to construct such a winding is to take a long bar of copper, and bend it as shown at *A*, Fig. 206. Then, if *ab* and *ed* are the lengths of the conductor in the slot, the bar may be opened out as in *B*, Fig. 206, if the winding is to be lap-wound, or as in Fig. 207, if the winding is to be wave-wound. Methods of computing the necessary length of the end-connections have been referred to on page 116, so that the required length of bar may be predetermined.

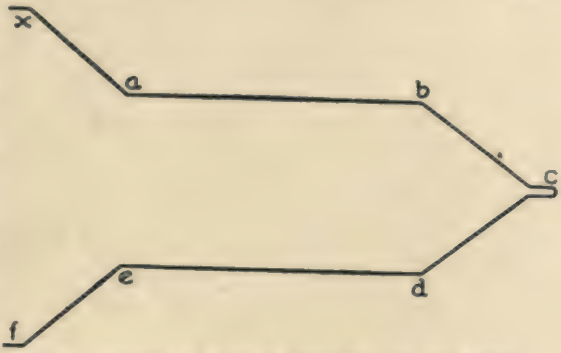


Fig. 207. Element of Wave Winding Formed from Strip.

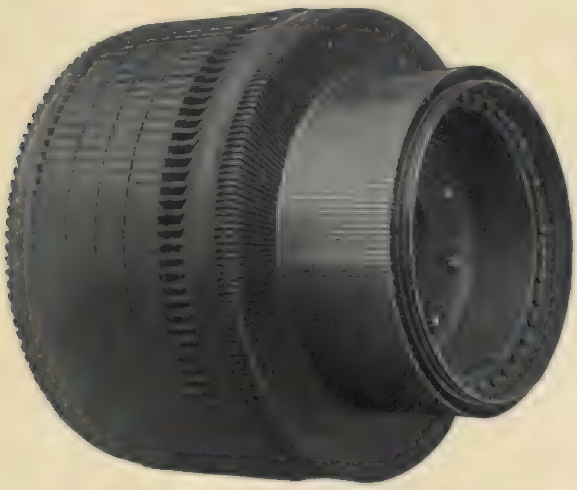


Fig 208. Armature of Triumph Generator.

In Figs. 208 and 209, finished armatures of this type are represented, while Fig. 210 illustrates these diagrammatically.

Thus far the windings have been described as formed of copper bars; but it is also possible to wind either of these types with wire, shaping the coils either before or after placing the wire in the slots.

Cases also occur where more than two layers of wire are necessary, either on account of the high voltage required, or to avoid harmful induction.

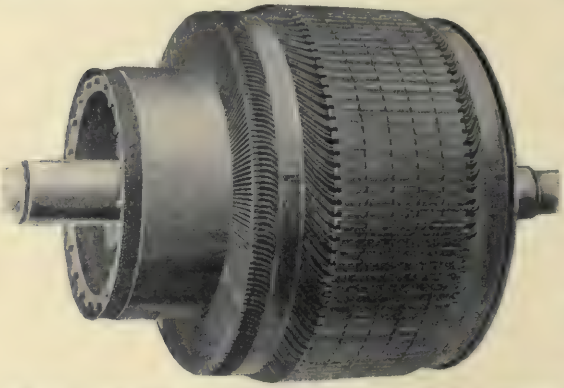


Fig. 209. Complete Armature of Crocker-Wheeler Company Engine-Type Generator.

Bastard windings is the name given to that class of armature windings whose end-connections, instead of being carried in toward the shaft in evolutes or elongated cylindrically, are partly inward and partly cylindrical. This has the effect of making the length of the armature parallel to the shaft shorter than with the pure barrel winding. It requires, however, special formers, and is applicable only to bar-wound armatures. On account of better ventilation, it is usual to combine a bastard winding at one end of the armature, with a barrel winding at the commutator end, as in Fig. 211; while Figs. 212, 213, 214 show the relation of this scheme to the two previously mentioned.

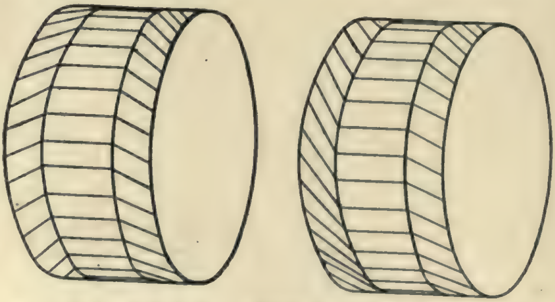


Fig. 210. Diagrammatic Representation of Barrel Winding.

Form-Wound Drum Windings. It was early found that hand-wound drums were both expensive in labor and unsymmetrical electrically. This resulted in the development of schemes for arranging the winding in coils on *formers,* and then laying these *formed coils* in their respective places upon the core-body. The individual sections of the winding are first wound and shaped upon a frame or former, the wire being plain cotton-covered; and each such section is again separately insulated by winding with tape, usually half-lapped; then baked, varnished, and baked again.

Alioth, according to the patent records, was the first to devise this plan. He was followed by Eickemeyer, who in 1888 patented a method of winding formed coils for evolute windings. This method attained almost universal use during the vogue of the evolute winding; and the first three stages in the construction of such a section are illustrated in Fig. 215; while Fig. 216 illustrates a later type of the former, and Fig. 217 a completed armature winding built up of such coils.

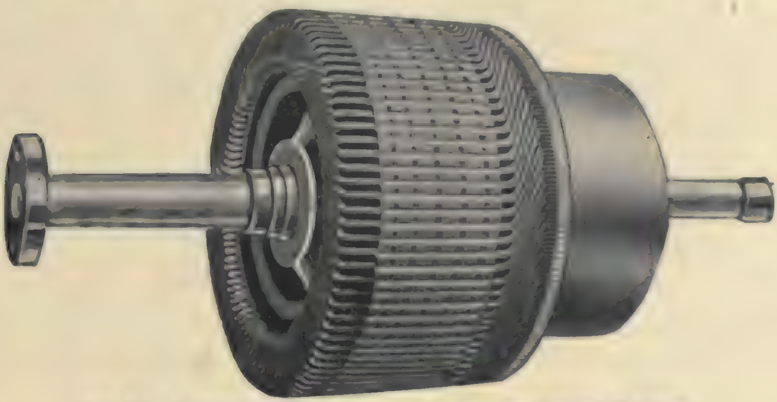


Fig. 211. Armature of Westinghouse Generator—Bastard Winding.

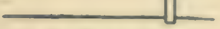


Fig. 212. Evolute-Wound Armature.

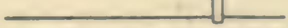


Fig. 213. Barrel-Wound Armature.

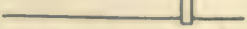


Fig. 214. Bastard-Wound Armature.

What the Eickemeyer coil accomplishes for the evolute winding, may be accomplished for the barrel winding by use of "straight-out" formers. Fig. 218 illustrates a simple former of this type, upon which a coil for a wave winding has been wound and then opened out. Figs. 212, 213, and 214 illustrate the three principal types of formed windings; while Figs. 205, 219, and 220 illustrate successive stages in the construction of a barrel-wound armature using formed coils.

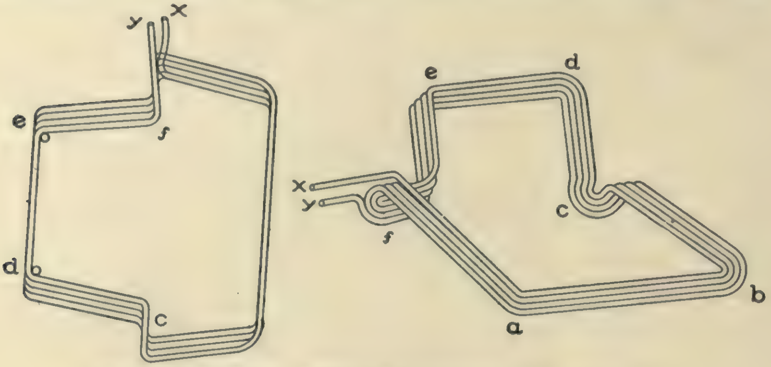


Fig. 215. Eickemeyer Former-Wound Coil, and Same Bent Up.

Ring Windings. These windings are almost always hand-wound, because the connections at the ends are not nearly so complicated as those of a drum-winding, and the winding is in general easily applied. Nevertheless care must be exercised, since the various sections are usually wound upon the core separately, the

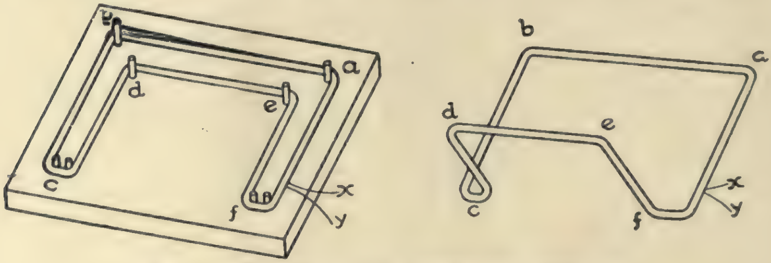


Fig. 216. Eickemeyer Coil on Former and Opened Out.

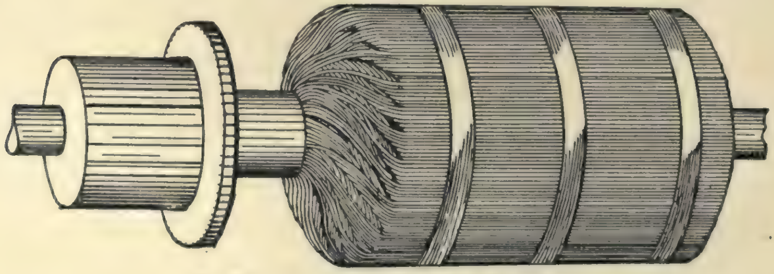


Fig. 217. Eickemeyer Armature, Complete.

ends being left projecting. A careless workman may connect them so that some may generate in opposition, thus reducing the terminal voltage of the machine; hence it is usual to tag the ends of the coils, indicating the beginning and end of each section. Fig. 221 illustrates a partially completed ring-wound armature, the core being made in two parts to facilitate winding.

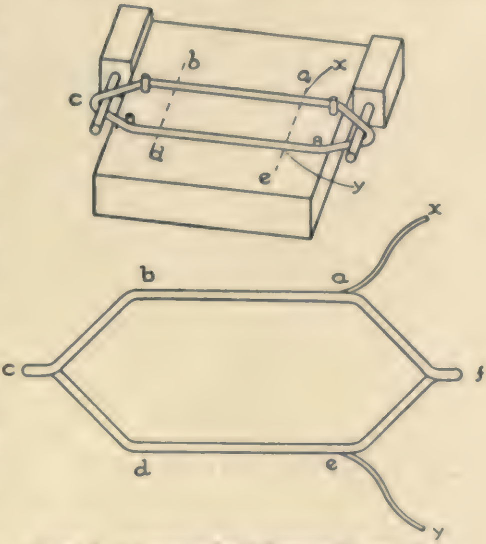


Fig. 218. "Straight-Out" Former-Wound Coil, and Coil Opened Out.

Arrangement of Conductors in Slots. Various methods of arranging the conductors in the slots have been mentioned. The most frequent plan in large continuous-current generators is that of putting them in two layers, either two or more in a slot. Form-wound coils lend themselves to the two-layer arrangement, which, however, is adapted to be used only with parallel-sided slots. Yet, by grouping the conductors three or four in a slot, as indicated in Fig. 222, or six in a slot, as in Fig. 223, T-shaped teeth can be employed. It must be remembered that, owing to the magnetic shielding of the teeth,

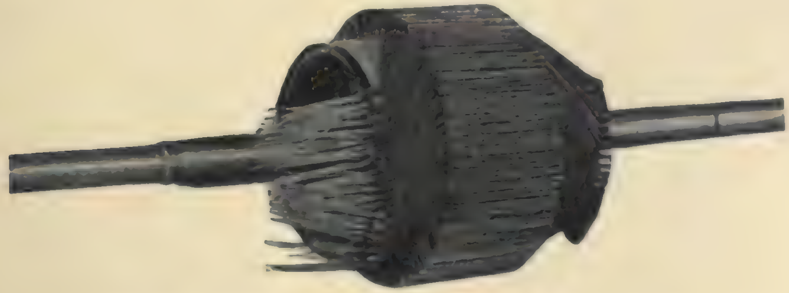


Fig. 219. Armature Body Showing Coils as Placed in Position.

the conductors are subjected practically to centrifugal force only. Unless the pole-faces are laminated, the top breadth of the slots must be kept very narrow (*i. e.*, not wider than 2½ times the length of the air-gap, because of eddy currents being otherwise generated in the pole-faces); also, if straight teeth are employed, they must be kept very narrow, otherwise the high flux-density required in the teeth for sparkless collection of current will not be attained.

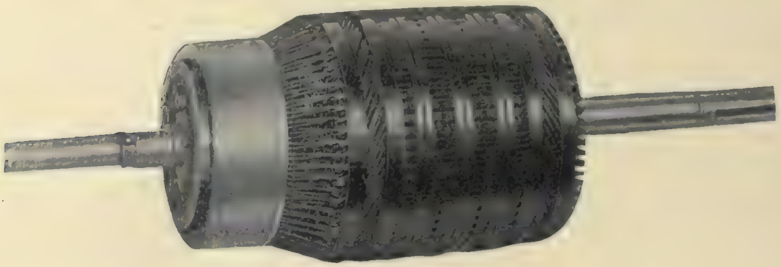


Fig. 220. Generator Armature, Complete.

All electric and magnetic considerations point to having the slots and teeth narrow and numerous; while mechanical considerations impose a limit upon the minimum width of teeth. Standard practice for parallel-wound armatures has had to choose a mean, and it is usual to put four conductors in a slot.

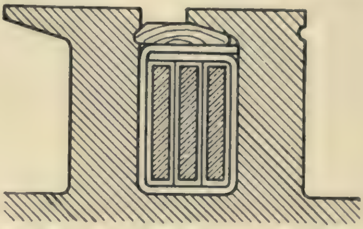


Fig. 222. Three Conductors Grouped in Slot.

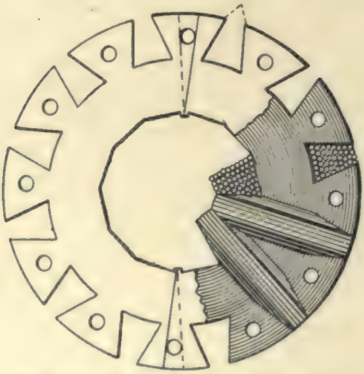


Fig. 221. Partially Completed Ring-Wound Armature.

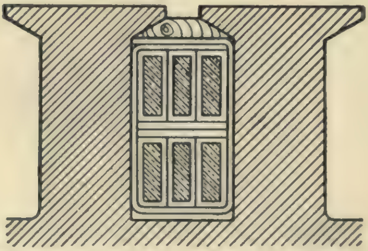


Fig. 223. Six Conductors Grouped in Slot.

CONSTRUCTION OF COMMUTATOR AND BRUSH-RIGGING

Commutator Bars. These are always made of copper; other metals, such as brass, iron, or steel, are not satisfactory, on account of pitting and burning. Rolled copper is preferable, because of its toughness and uniform texture; but in some cases, on account of the shapes necessitated by different methods of connection to the armature conductors and various clamping devices, the segments are either cast or drop-forged, the latter being at present the commercial type.

In order to secure a good fit, the cross-section of the bars should be properly tapered according to the number that go to make up the whole circumference. It is obvious that if the number of segments = 360, each segment plus its insulation (on one side) should have a taper of 1 degree; while if $K = 36$, the taper would be 10 degrees. It is not practicable, however, to use mica insulation that has not parallel faces; hence the segment is tapered, and any defect in the taper of the latter cannot be made good with insulation. It is found, however, that when the segments exceed 150, bars of the same taper can be used in constructing a commutator having either two more or two less than the designed number.

Insulation. It is needful to have good insulation between each bar and its neighbor, and especially good insulation between the bars and the sleeve or hub around which they are mounted, as well as between the bars and the clamping devices that hold them in place, since the voltage between bars is not so great as that between the bars and the metal-work of the machine. It is essential that the insulating material be such that it will not absorb oil or moisture; hence asbestos, plaster, and vulcanized fibre are inadmissible. The end insulation rings may be of micanite, or, if for low voltage, of that preparation of paper pulp known as *press-board* or *press-spahn*. The conical rings are usually built of micanite moulded under pressure while hot. Fig. 224 illustrates such an end-ring, cut away to show its section.

Commutators using air-gaps between the segments as insulation have been tried; but, excepting in the case of arc-lighting machines where the segments are few in number and the air-gap large, they have not proven successful, owing to trouble in keeping the gaps free from metallic dust.

It is of importance that the mica selected for insulating the bars from one another should be soft enough to wear away at the same rate as the copper bars, and not project above the segments. Amber mica, soft and of rather cloudy color, is preferred to the harder clear white or red Indian variety. The usual thicknesses are as given in Table XIII.

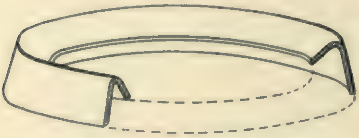


Fig. 224. End Insulation Ring of Commutator.

Commutator Construction. For small machines a common construction is that shown in Fig. 225. The commutator segments

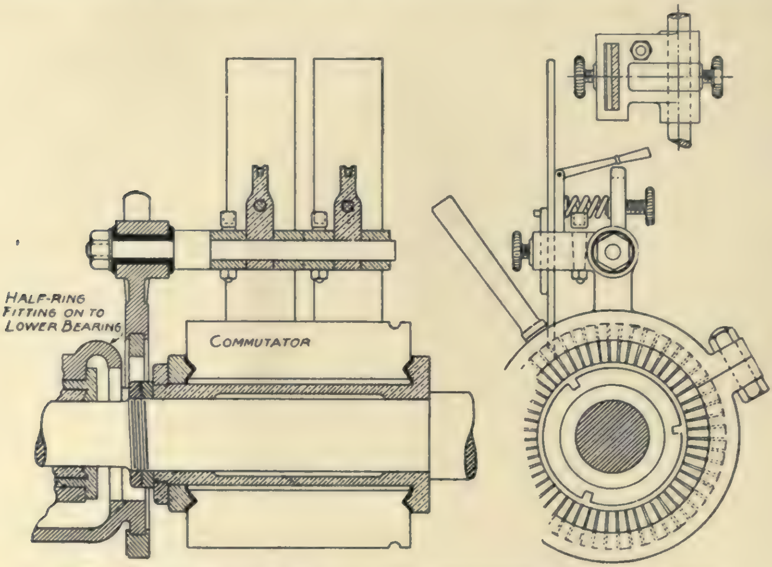


Fig. 225. Common Method of Commutator Construction for Small Machines.

TABLE XIII

Thickness of Commutator Insulation

VOLTAGE OF MACHINE	THICKNESS OF MICA	
	Between neighboring segments	Between segments and shell, and between segments and clamping device
Less than 150	0.020 to 0.03 in.	0.06 to 0.10 in.
Less than 300	0.025 to 0.04 in.	0.08 to 0.13 in.
Less than 1,000	0.04 to 0.06 in.	0.10 to 0.16 in.

are secured between a bushing or hub and a clamping ring, the latter being mounted on the hub, and forced to grip the bars by means of a nut on the hub or by bolts passing through the ring and hub, as in Fig. 226. The ends of the bars are beveled so that the ring and bushing draw the segments closer together on tightening.

The hub, in small machines, is usually of cast iron keyed to the shaft; but in large machines, the commutator is built upon a strong flange-like support or shell, bolted to the armature spider, as indicated in Fig. 208 and Fig. 227, or mounted on a separate spider secured to the shaft, as in Fig. 228.

When drawn copper strip is used, the design should be such that the available surface for the brushes takes up nearly the whole length of the bar, and the beveled ends should be as simple as possible. With drop-forged segments, this is not so important.

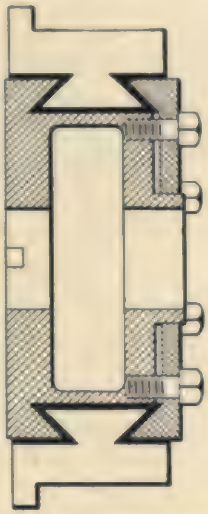


Fig. 226. Construction of Commutator of Medium Size.

In building commutators it is usual to assemble the bars to the proper number, with the interposed pieces of mica, clamping them temporarily around the outside with a strong iron clamp, or forcing them into an external steel ring under hydraulic pressure. They are then put into a lathe, and the interior surface is bored out, after which the ends are turned up, with the angular hollows to receive the clamping pieces. The whole is then mounted with proper insulation, upon the sleeve, and the clamping end-pieces are screwed up. It is then heated, and the clamps still further tightened up, after which the temporary clamp or ring is removed and the external surface turned up.

Commutator Risers. Connection is made with the armature conductors by means of radial strips or wires sometimes called *risers*, which are inserted into a cut at the corner of each bar and firmly held there by a screw clamp and solder. Figs. 229, 230, and 231 illustrate various modes of making connection to the commutator bar.

These risers are connected to the armature winding in several different ways, as indicated in Fig. 232.

In some evolute windings no risers are needed, the ends of the evolute being fastened to the commutator as indicated in Fig. 204. Similarly, in the case of barrel-wound armatures, no risers are needed if the commutator diameter is very nearly that of the armature.

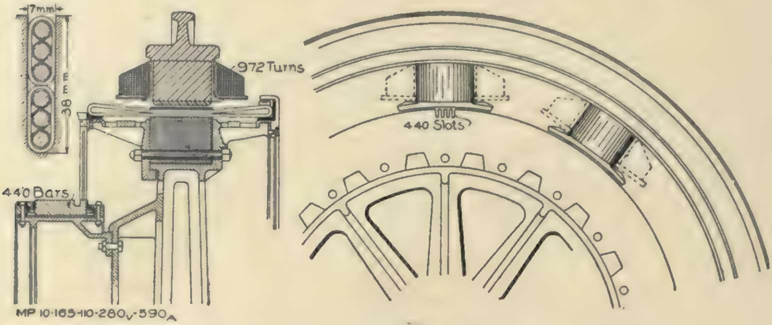


Fig. 227. Ten-Pole Lighting Generator of the Oerlikon Company. Commutator support bolted to armature spider.

Brushes and Brush-Rigging. As we have seen on page 42, carbon brushes are almost the only type that are now considered. Their shape depends upon the type of brush-holder selected, and upon whether the brushes are applied to the commutator semi-tangentially or radially. Fig. 233 illustrates various shapes.

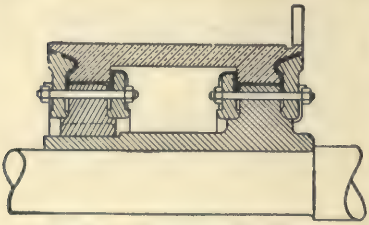


Fig. 228. Commutator for Large Currents.

The mechanism for holding the brushes must fulfil the following requirements:

1. The brushes must be held firmly against the commutator, while allowing them to follow any irregularity in the contour of the latter without jumping away.

2. The mechanism must permit of the brushes being withdrawn while the commutator is rotating, and must feed them forward as required.

3. Spring pressure must be adjustable, *and the spring must not carry current.*

4. The springs must not have too great inertia, in order that they may readily fulfil condition 1, in regard to following the commutator.

5. Insulation must be very thorough.

6. The mechanism must be so arranged as to permit of the position of the brushes being shifted.

7. All parts must be firm and strong, so as not to permit of the brushes chattering as the result of vibration while running.

The commercial forms of holders for carbon brushes may be classified under three types:

1. **Hinged structures.**
2. **Parallel spring holders.**
3. **Reaction holders.**

Fig. 234 illustrates a hinged brush-holder, and an arm holding several. The carbon moves in a light frame, being held against the commutator by a spring whose tension may be adjusted. Connection between the brush and the holder is made by means of a flexible lead, tinned and laid in a slot in the upper part of the carbon. A metal cap placed over the top and sweated in place makes a permanent contact. This is shown by the two illustrations of the brush.

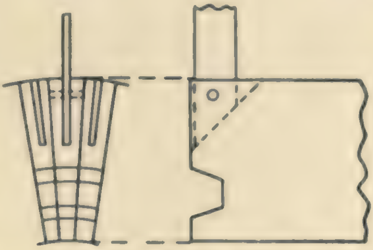


Fig. 229.

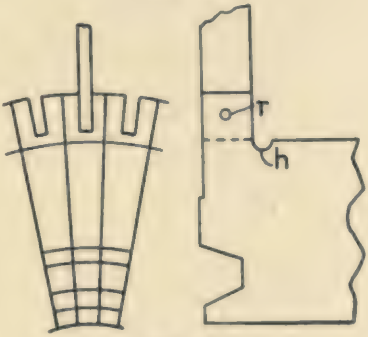


Fig. 230.

Fig. 235 illustrates a parallel-movement type, also depicted in Fig. 144, on page 126. The brush is held firmly in the holder by a clamping screw, the whole arrangement then being pressed against the commutator by the spring, whose tension may be varied by means of the adjusting screw. Connection is made between the brush and the stationary part of the holder, by means of two sets of rolled-copper leaves which at the same time act as flexible joints.

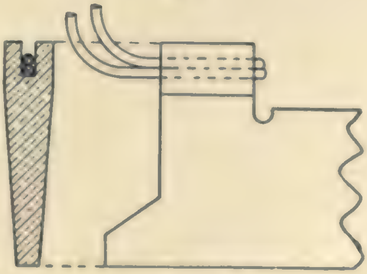


Fig. 231.

Methods of Connecting Commutator Risers to Commutator Bars.

In Fig. 236 is illustrated a reaction type of brush-holder. The brush *C* is pressed against the commutator by the adjustable spring *L*, the holder *B* being secured firmly to the rocker-arm *P* by means of the set-screw *g*. The brush is furnished with a dovetail-shaped projection along its entire inner edge, this projection fitting into a groove in the face of the holder *B*.

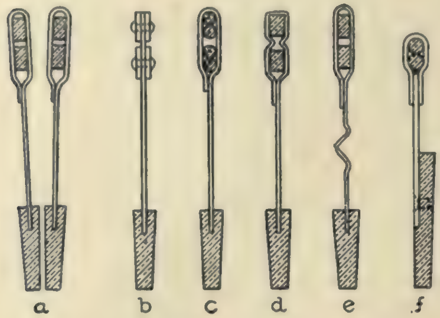


Fig. 232 Methods of Connecting Commutator Risers to Armature Winding.

Rockers and Rocker-Arms. For small machines, the rocker is usually clamped upon a shoulder turned upon the bearing pedestal as indicated in Fig. 225. For large multipolar generators, the rocker arms—that is, the rods on which the brush-holders are held—are fixed at equidistant points around a cast-iron rocker-ring, which is itself supported on brackets projecting from the magnet-yoke. This construction is indicated in Fig. 237.

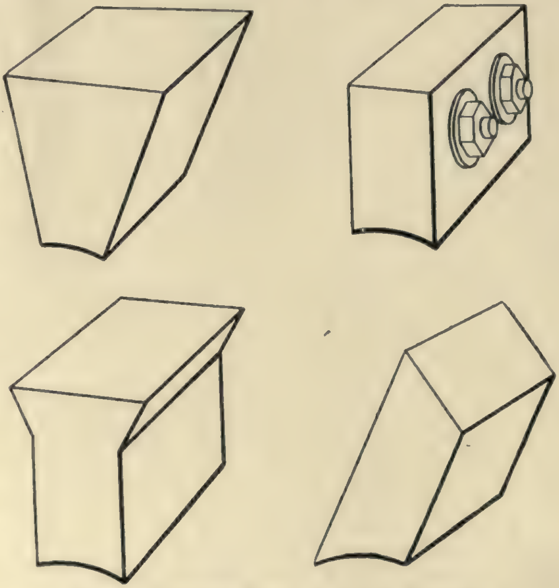


Fig. 233. Various Forms of Carbon Brushes.

Sweating Lugs and Terminal Thimbles. Among the details of brush-gear are the contrivances for bringing the current to and from the brush-pillars or rocker-rings. This is usually accomplished by the use of large, flexible connections made of stranded copper wire well insulated. It is necessary that all such flexible leads should make good contact at their ends to solid metallic pieces. On the rocker are usually provided sweating lugs (Fig. 238) of copper or brass, into which the ends of the flexible cable are sweated. Their other ends are then sweated into suitable thimbles or sockets on a terminal board (Fig. 239) which is attached to some convenient point on the magnet-frame.

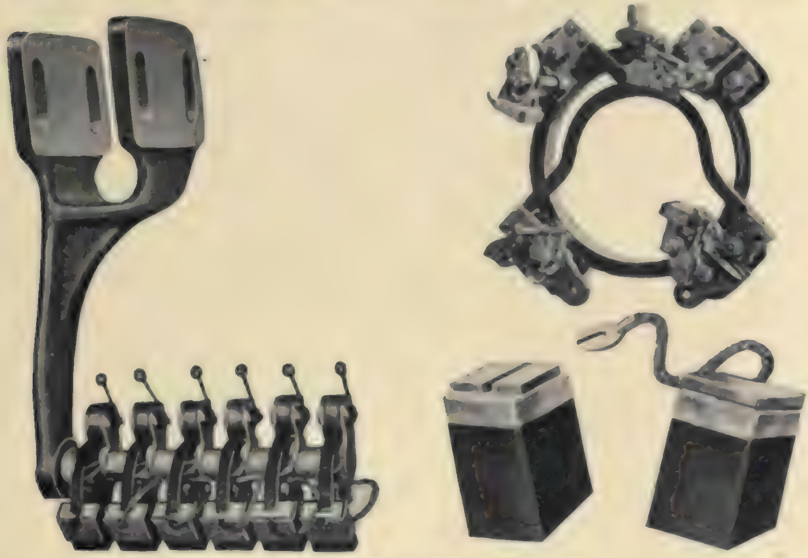


Fig. 234. Brush-Rigging and Brushes.

CONSTRUCTION OF MECHANICAL PARTS

Bearings and Pedestals. Bearings for generators are always made divided, so that the armature can be lifted into and out of its bed, and usually with steps of brass or gun-metal seated in an appropriate pedestal. Often the pedestal is made in two parts bolted together, the joint occurring at the level of the under side of the armature to admit of the latter being withdrawn, and

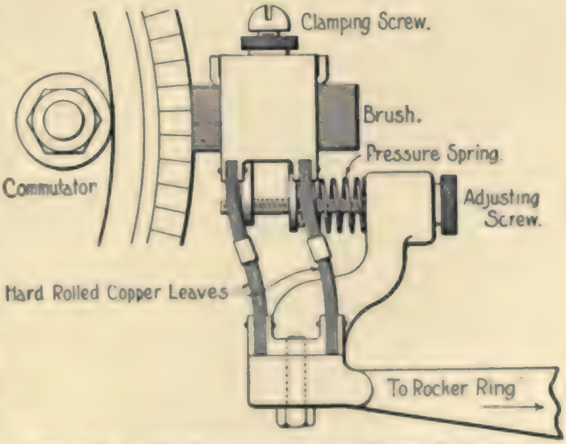


Fig. 235. Parallel-Movement Type of Brush-Holder.

affording a resting point during removal. Where long bearings are used, they are sometimes made of cast iron with a lining of Babbitt or similar soft metal, such anti-friction metal being cast in hollows in the cast-iron step prepared for that purpose. In the case of generators whose armatures are mounted on the end of the engine shaft for direct driving, only the outboard bearing (if any) is provided by the generator manufacturer, the other being part of the engine; while in some cases the armature is overhung and requires no outer bearing, as in Fig. 240.

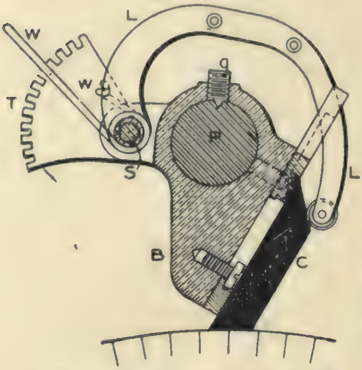


Fig. 236. Reaction Type of Brush-Holder.

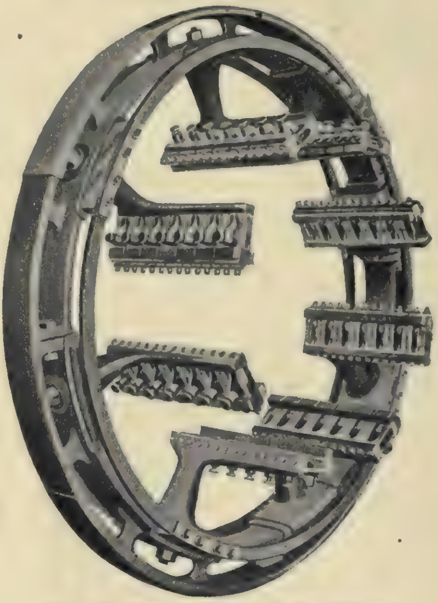


Fig. 237. Rocker-Ring and Brush-Gear. Crocker-Wheeler Company.

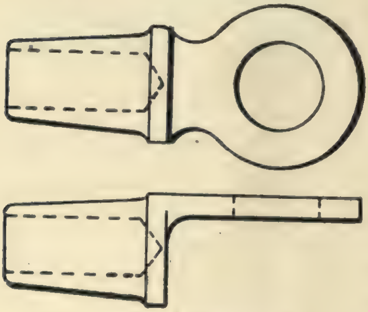


Fig. 238. Sweating Lug.

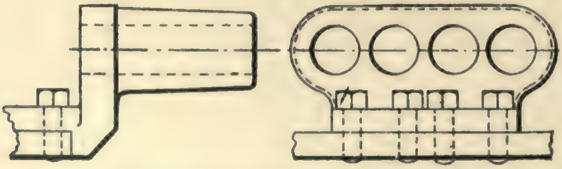


Fig. 239. Sweating Thimbles on Terminal Board.

In cases where the bearing is very long, it is necessary that the bearing be made self-aligning, by providing it with an enlarged central portion of spherical shape (Fig. 241), held in a spherical seat formed in the pedestal by turning, milling, or by casting Babbitt or other fusible metal around it, thus allowing the bearing to adjust itself to the exact direction of the shaft. The upper half of the box can be taken off to facilitate renewal, etc. Fig. 242 also illustrates a bearing of this type; while Fig. 243 illustrates a simple bearing showing the division of the pedestal.

Ball-bearings have recently been applied to generators and motors—particularly the latter, on account of their low static friction. Where space and low friction losses are essential, and where there is little lateral dragging due to belts, these bearings have given excellent results.

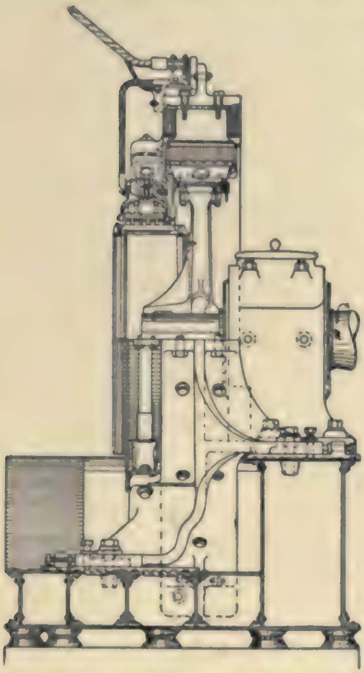


Fig. 240. Direct-Connected Generator with Overhung Armature.

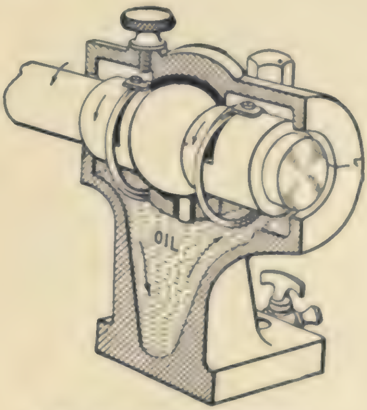
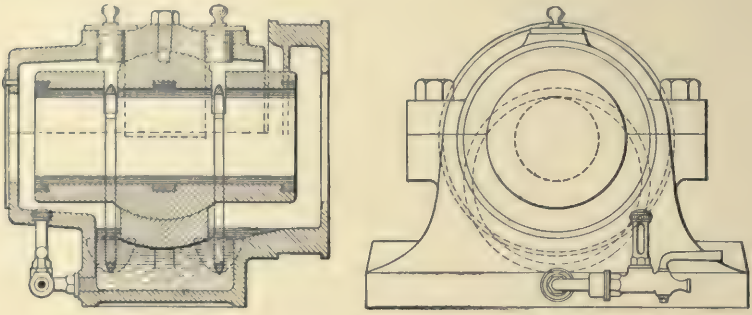


Fig. 241. Self-Oiling Bearing.

Figs. 244 and 245 show ball-bearing mountings for horizontal and vertical motors, respectively. The section at the left of Fig. 244 is for the pulley end, while that at the right is for the commutator end. Fig. 245 shows a form of mounting for vertical motors. It is differentiated from the horizontal type, simply by the introduction of devices for keeping sufficient lubricant in the bearing to permit the balls always to drop through it. Fig. 246 illustrates a side view of a portion of one of these bearings, showing the steel balls with elastic separators between them. The separators contain felt plugs which incidentally store up lubricant to guard the bearings for a time against neglect.



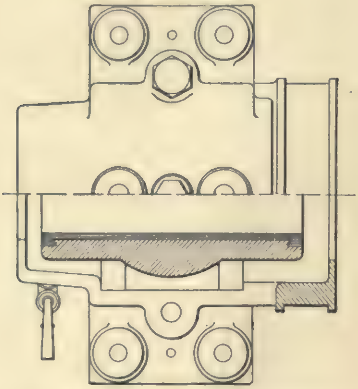


Fig. 242. Self-Aligning Spherical Bearing.

An advantage that attends the use of these bearings is that the feature of non-wear permits making them oil-proof and dust-proof without the usual added complications.

Lubricators. Provision must be made for supplying the bearings with oil or grease; and for this purpose it is usual to provide an oil-well in the hollow casting of the pedestals, into which the oil drains from the brasses. Self-lubricating bearings are now almost uni-

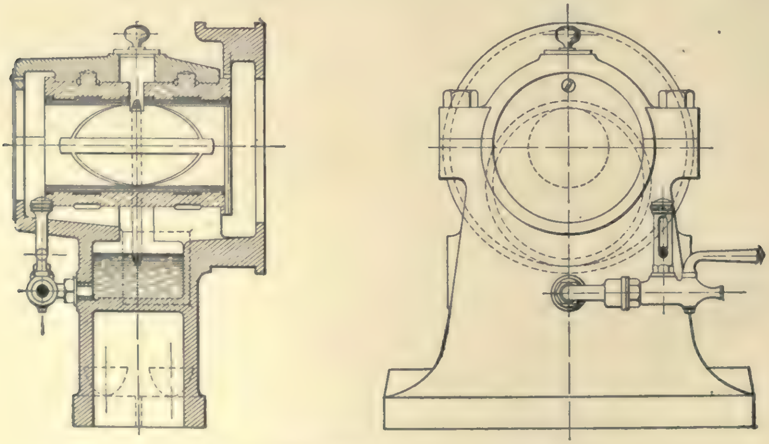
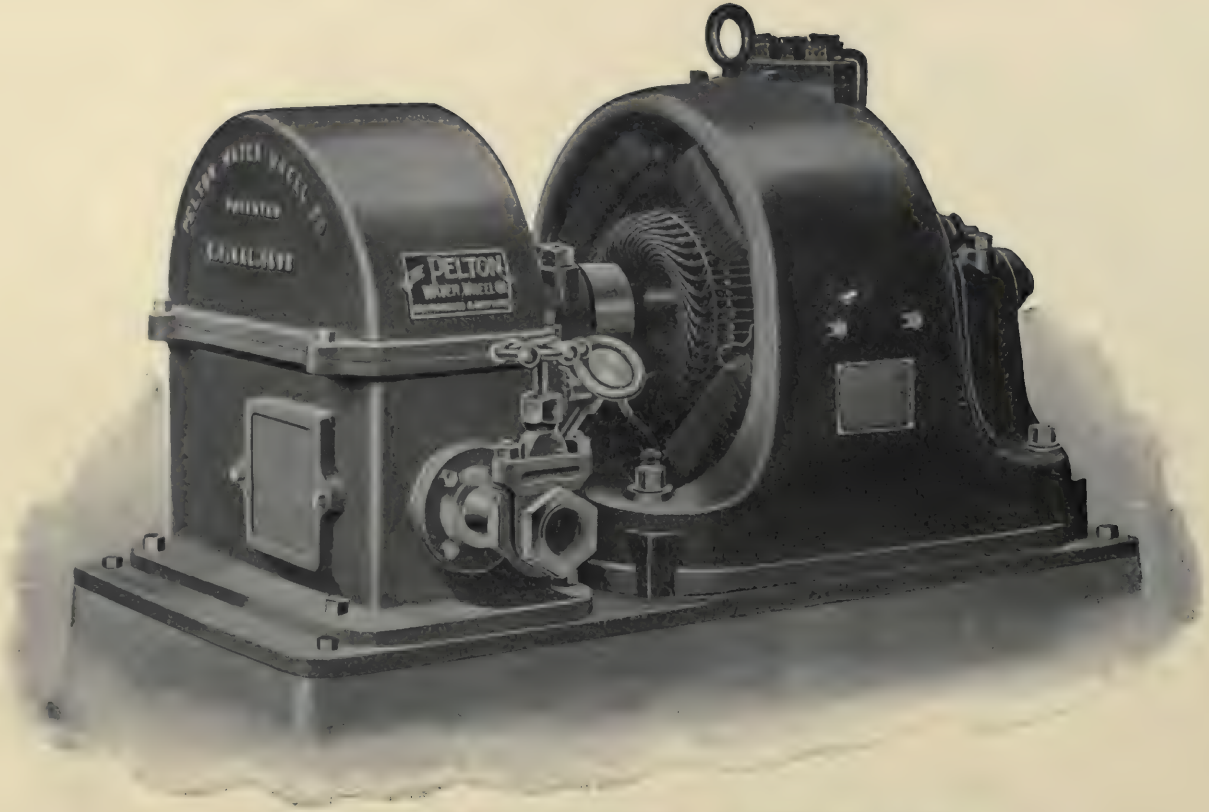


Fig. 243. Self-Oiling Bearing for Commutator End.



WATER MOTOR MOUNTED ON OVERHANG OF GENERATOR SHAFT.

Pelton Water Wheel Company.

versal in the ordinary types of generators. Fig. 241 illustrates one of this type. The rings here shown revolve with the shaft, and feed the latter with oil, which they continuously bring up from the reservoir below. The dirt settles to the bottom and the upper portion of the oil remains clean for a long period, after which it is drawn off through the spigot, and a fresh supply poured in through openings provided in the top. The latter are often located directly over the slots in which the rings are placed, so that the bearings can be lubricated directly by means of an oil-cup, if the rings fail to act or the reservoir becomes exhausted.

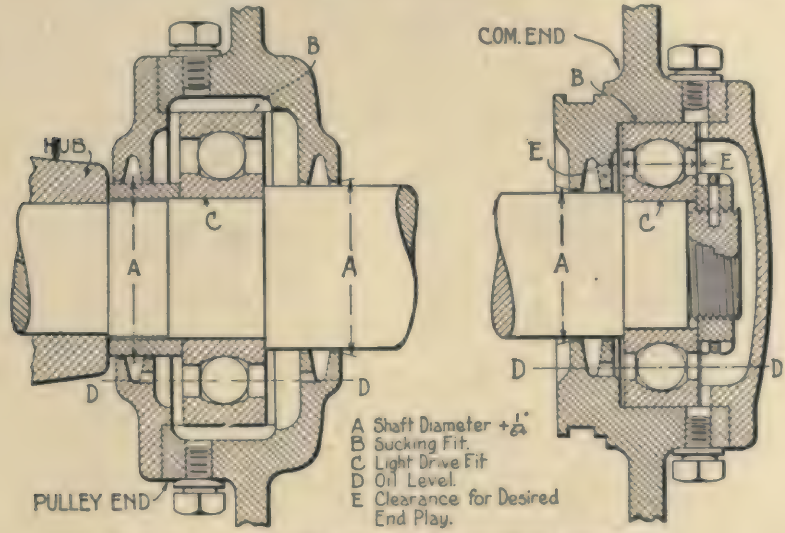


Fig. 244. Ball-Bearing Mounting for Horizontal Motor-Shaft.

Bed-Plates. In most cases a generator is supplied with a cast-iron base or bed-plate which supports the bearings and magnet-yoke. It consists of a simple box, open at the bottom in order to give stiffness without great weight. It must be sufficiently rigid to withstand any reasonable strain without bending.

In belt-connected machines the iron base usually rests upon rails bolted to the foundations, the base being arranged to slide back and forth upon the same in order to regulate the tension of the belt, by means of set-screws. A direct-connected generator of small or medium size is usually bolted to an extension cast-iron base or sub-base of the engine. In some cases a generator and engine are coupled

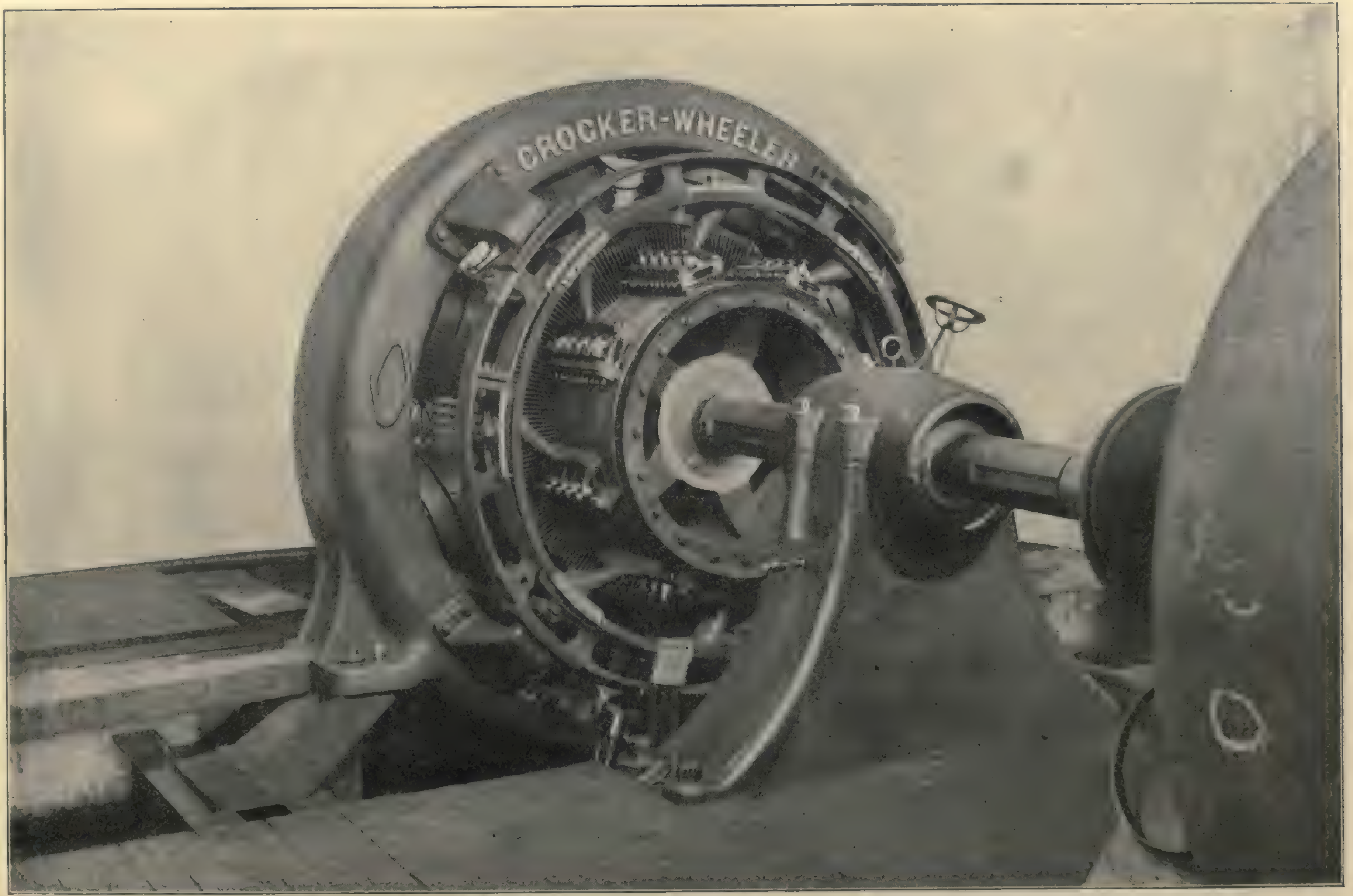


Fig. 247. Crocker-Wheeler Generator of Type whose Construction is Described in Detail in Text. 150 Kilowatts, 250 volts, at 225 r. p. m.

together, each being complete in itself and having its own base. Very large direct-connected generators and engines are set on separate foundations.

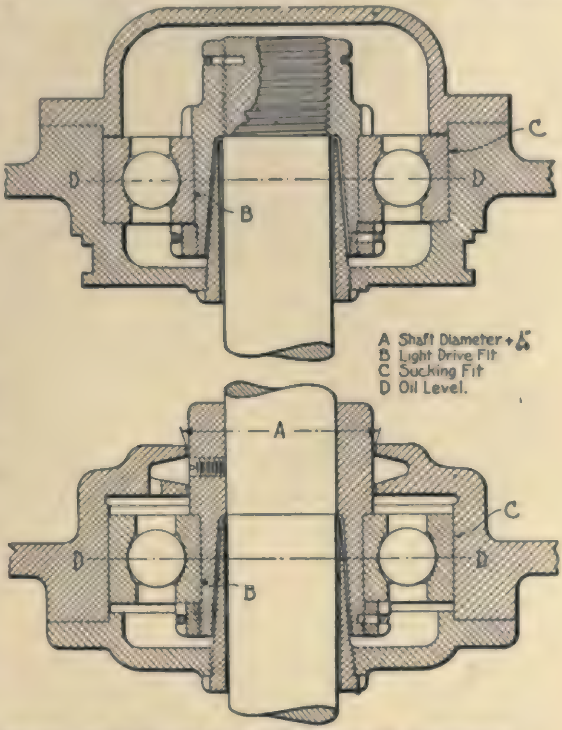


Fig. 245. Ball-Bearing Mounting for Vertical Motor-Shaft.

DESIGN OF CONTINUOUS-CURRENT GENERATORS

The design of a generator may be considered in the light of a problem in which it is required to produce a machine which shall operate satisfactorily at all loads from no load to 50 per cent overload, which shall be efficient, and conform to the conditions of prescribed speed, voltage, and current output. This involves the theoretical and practical features already considered. In order to guide the student, it has been thought advisable to follow through the complete design of a particular modern generator. No hard-and-fast rules can be given covering all cases which come up, so that the tables given below should be used only as guides, each machine requiring a separate solution of the general problem.

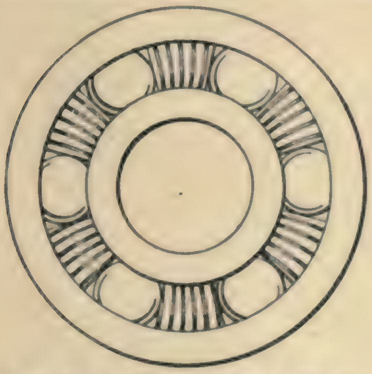


Fig. 246. Side View of Ball-Bearing Mounting, Showing Steel Balls with Elastic Separators between them.

Specifications. To design a continuous-current generator, it is

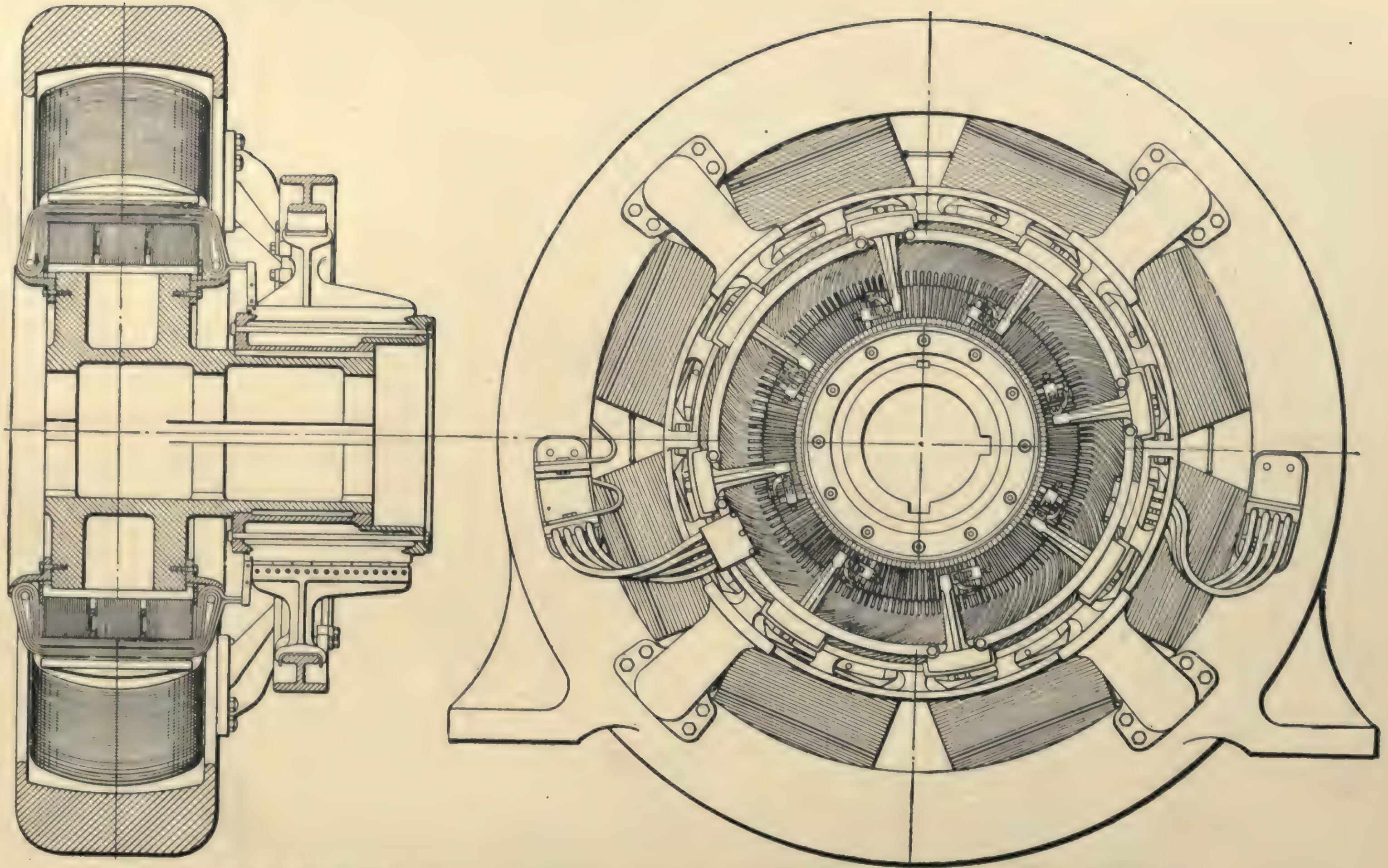


Fig. 248. Front and Side Elevation of Columbia University Dynamo, Size 280. Crocker-Wheeler Electric Company.

sufficient to be given the capacity of the machine in kilowatts, the terminal voltage at rated load (also at no load, if compound-wound), and the speed of rotation of the armature, although Table XIV will supply the latter quantity, if absent. Let us assume for the purposes of this design:

Kw. output	150
Terminal volts, rated load	250
Terminal volts, no load	240
Armature r. p. m.	225

The generator is direct-connected to the engine driving it, and it must be compound-wound in order that its terminal voltage at rated load shall be 10 volts higher than at no-load.

TABLE XIV

Relation of Output to Speed of Direct-Current Generators

CAPACITY (in kw.)	DIRECT-CONNECTED GENERATORS r. p. m.	LOW-SPEED BELTED GENERATORS r. p. m.	HIGH-SPEED BELTED GENERATORS r. p. m.
1	....	700 to 1,400	1,400 to 2,800
2	....	670 to 1,250	1,250 to 2,450
5	400 to 800	640 to 1,170	1,170 to 2,200
10	340 to 480	610 to 1,050	1,050 to 1,950
15	305 to 415	580 to 960	960 to 1,770
20	270 to 385	550 to 900	900 to 1,650
30	230 to 355	510 to 800	800 to 1,450
40	200 to 340	480 to 740	740 to 1,320
60	175 to 325	460 to 660	660 to 1,110
80	140 to 310	450 to 620	620 to 975
100	120 to 290	440 to 590	590 to 850
150	110 to 250	420 to 540	540 to 700
200	100 to 230	395 to 495	495 to 625
250	92 to 205	380 to 460	460 to 570
300	86 to 180	360 to 435	435 to 520
350	80 to 160	345 to 410	410 to 475
400	76 to 140	325 to 380	380 to 440
500	70 to 124	295 to 335	335 to 380
600	66 to 112	275 to 300	300 to 325
700	62 to 105	....	....
800	60 to 100	....	....
1,000	59 to 92	....	....
1,200	58 to 88	....	....
1,400	56 to 86	....	....
1,600	55 to 84	....	....

Since the generator is rated at 150 kw. at 250 volts, the rated load current will be:

$$\frac{150 \times 1{,}000}{250} = 600 \text{ amperes.}$$

Number of Poles. We must next decide upon the number of poles. This may be fixed either with a view to keeping down the iron losses in the armature, or to keeping the current collected per brush set low. In the former case, the frequency of magnetic reversal should not exceed 20 per second in shunt-wound machines, and 25 per second in compound-wound machines. In the second case, in order that the current may be commutated sparklessly, not more than 200 amperes ought be collected by each brush set; that is, the current output of the machine, divided by the number of poles, should not exceed 100.

From the first criterion, we find (since the magnetism of any part of the armature core undergoes a reversal as it passes each pole), for the number of poles:

$$p \geqq \frac{25 \times 60}{\text{r.p.m.}} = \frac{25 \times 60}{225} = 7$$

$$\geqq 7.$$

And from the second criterion:

$$p \geqq \frac{600}{100} \geqq 6.$$

To be quite sure of avoiding trouble as to sparking, and since an odd number of poles cannot be employed, let us take 8 poles, which, as we see from Table XV, is good practice for this size and type of machine.

TABLE XV

Relation of Capacity and Type to Number of Poles

Type	Output in Kilowatts	Number of Poles
Direct-Connected	0 to 2,030	4
	15 to 400	6
	90 to 400	8
	200 to 900	10
	300 to 1,800	12
	600 to 2,200	14
	800 to 2,500	16
Low-Speed, Belted	0 to 600	4
	15 to 600	6
High-Speed, Belted	0 to 20	2
	0 to 200	4
	60 to 800	6

Diameter and Length of Armature. The diameter of armature is limited by the peripheral speed allowable (Table XVI). It is also

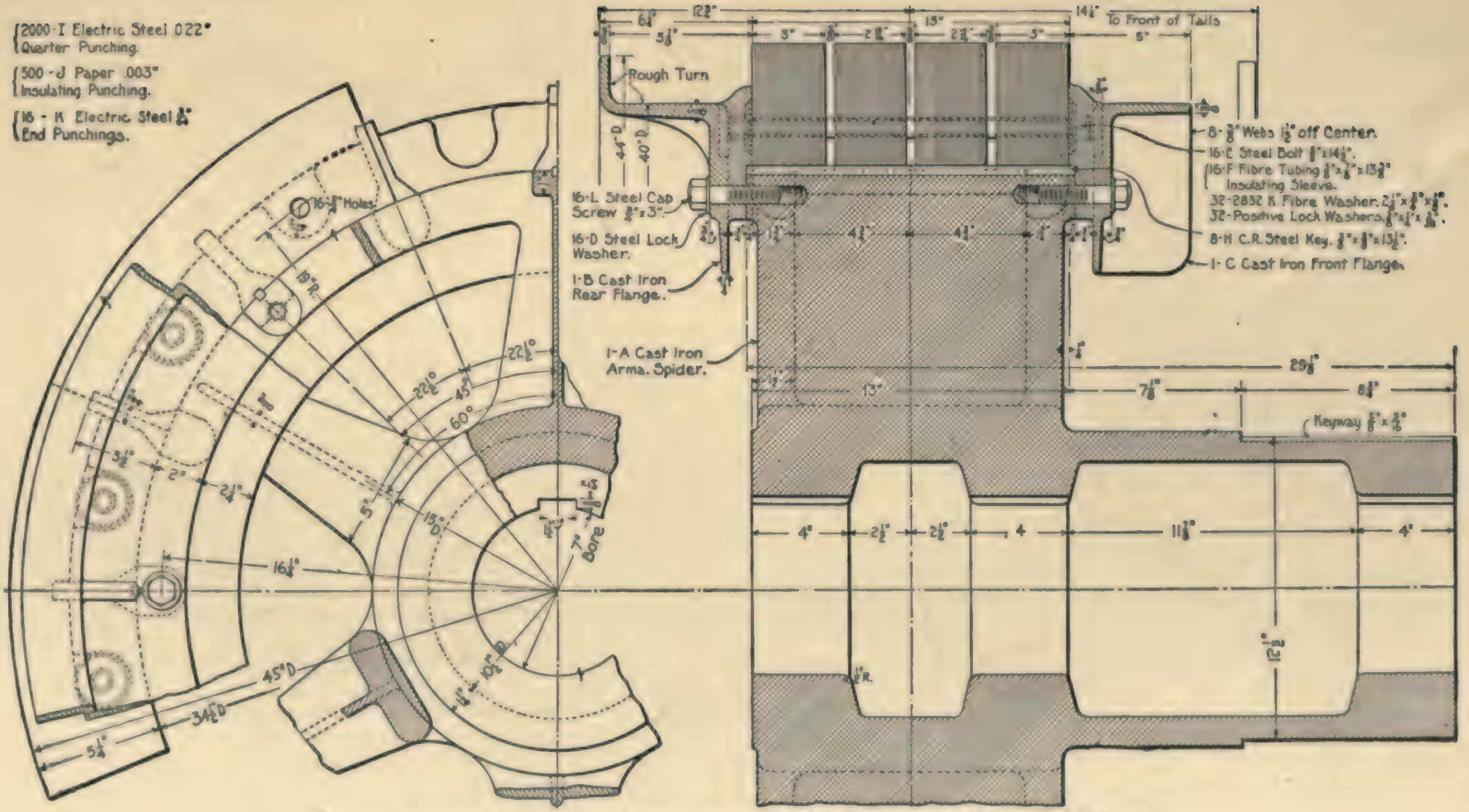

2000-I Electric Steel .022" Quarter Punching.
500-J Paper .003" Insulating Punching.
16-K Electric Steel End Punchings.
Rough Turn
16-L Steel Cap Screw × 3".
16-D Steel Lock Washer.
1-B Cast Iron Rear Flange.
1-A Cast Iron Arma. Spider.
To Front of Tails
8- Webs off Center.
16-E Steel Bolt × 14½".
16-F Fibre Tubing Insulating Sleeve.
32-2832 K Fibre Washer.
32-Positive Lock Washers.
8-H C.R. Steel Key.
1-C Cast Iron Front Flange.
Keyway
16 Holes
19"R.
7" Bore
45°D
34½"D
15"D
10½"D
60°
45°
22½°
13"
3"
5"
4"
4
2½"
2"
16¼"
5¼"
29⅝"
7⅛"

Fig. 249. Details of Armature and Spider of Generator whose Construction is Described in Text.

dependent upon the size of the magnet-poles and their number, the size, number, and arrangement of the armature conductors, and the output of the machine, the length being also a function of these quantities. Various empirical formulæ have been proposed for computing the length and diameter of armatures, but they all contain constants whose values must be learned by experience.

TABLE XVI

Peripheral Velocities of Direct-Current Armatures

Type of Generators	Peripheral Speeds in Feet per Minute		
	Minimum	Mean	Maximum
Bipolar high-speed, belted	2,000	3,000	3,500
Multipolar high-speed, belted	3,500	4,000	5,500
Multipolar slow-speed, belted	2,000	2,800	3,500
Direct-connected	1,800	2,400	3,300

For this reason it has been thought more advisable to append tables giving current practice in regard to the diameters and lengths of armatures, trial values being selected from these.

TABLE XVII

Diameters of Belted Multipolar Armatures *

Capacity (kilowatts)	Outside Diameter (in inches)			Ratio of Length to Diameter		
	Minimum	Mean	Maximum	Minimum	Mean	Maximum
1	4	7	10	0.36	0.65	0.80
2	5	8	11	0.36	0.64	0.80
5	6	9	12	0.36	0.63	0.80
10	8	11	15	0.35	0.62	0.80
20	11	14	19	0.34	0.59	0.80
30	14	17	23	0.33	0.56	0.75
50	17	21	29	0.31	0.52	0.71
75	20	25	35	0.28	0.48	0.67
100	22	29	40	0.26	0.44	0.63
150	26	34	46	0.23	0.40	0.58
200	30	38	51	0.22	0.38	0.55
300	34	44	60	0.21	0.36	0.52
400	38	49	65	0.20	0.34	0.50
500	40	54	66	0.20	0.32	0.49
600	43	57	68	0.19	0.30	0.48

* It is to be noted that for any given output and speed, the product of the diameter by the length of the armature is practically a constant.

In the design which we are considering, let us assume a peripheral velocity of say 2,650 feet per minute. At the required armature rotative speed of 225 r. p. m., this will give us a diameter of

$$\frac{2{,}650 \times 12}{225 \times \pi} = 45 \text{ in.},$$

which we see by Table XVIII to be about right. Assuming a length 29 per cent of the diameter, we get 45 in. × 0.29 = 13 in.

TABLE XVIII

Diameters of Direct-Connected Armatures *

Capacity (kilo-watts)	Outside Diameter (in inches)			Ratio of Length to Diameter		
	Minimum	Mean	Maximum	Minimum	Mean	Maximum
5	15	20	25	0.15	0.25	0.50
15	17	22	27	0.15	0.25	0.48
25	18	24	29	0.15	0.25	0.46
50	21	27	34	0.15	0.25	0.44
75	24	30	39	0.15	0.25	0.42
100	26	34	44	0.15	0.25	0.40
150	31	41	52	0.14	0.24	0.38
200	35	47	61	0.14	0.23	0.36
300	44	58	77	0.14	0.22	0.34
400	52	69	89	0.14	0.21	0.32
500	60	80	100	0.13	0.20	0.30
600	67	87	108	0.13	0.19	0.28
700	74	95	115	0.13	0.18	0.26
800	80	100	121	0.13	0.17	0.24
900	87	107	127	0.12	0.16	0.23
1,000	92	112	131	0.12	0.16	0.22
1,200	100	120	140	0.12	0.15	0.21
1,400	116	130	148	0.11	0.15	0.20
1,600	122	133	152	0.11	0.14	0.19

Magnetic Flux per Pole. After deciding upon the number of poles (p), the diameter (d), and the length (l) of the armature, we may obtain a trial value for ϕ, the magnetic flux per pole entering or leaving the armature, by assuming proper values for the magnetic flux-density in the air-gap and the surface of the armature covered by the poles. The flux-density in the air-gap varies from 40,000 lines to 55,000 lines per square inch (Table IV), while a usual value for the fraction of the armature covered by the poles is $\Psi = 0.75$. We may then write:

$$\phi = B_g \times d \times \pi \times l \times \Psi \div p.$$

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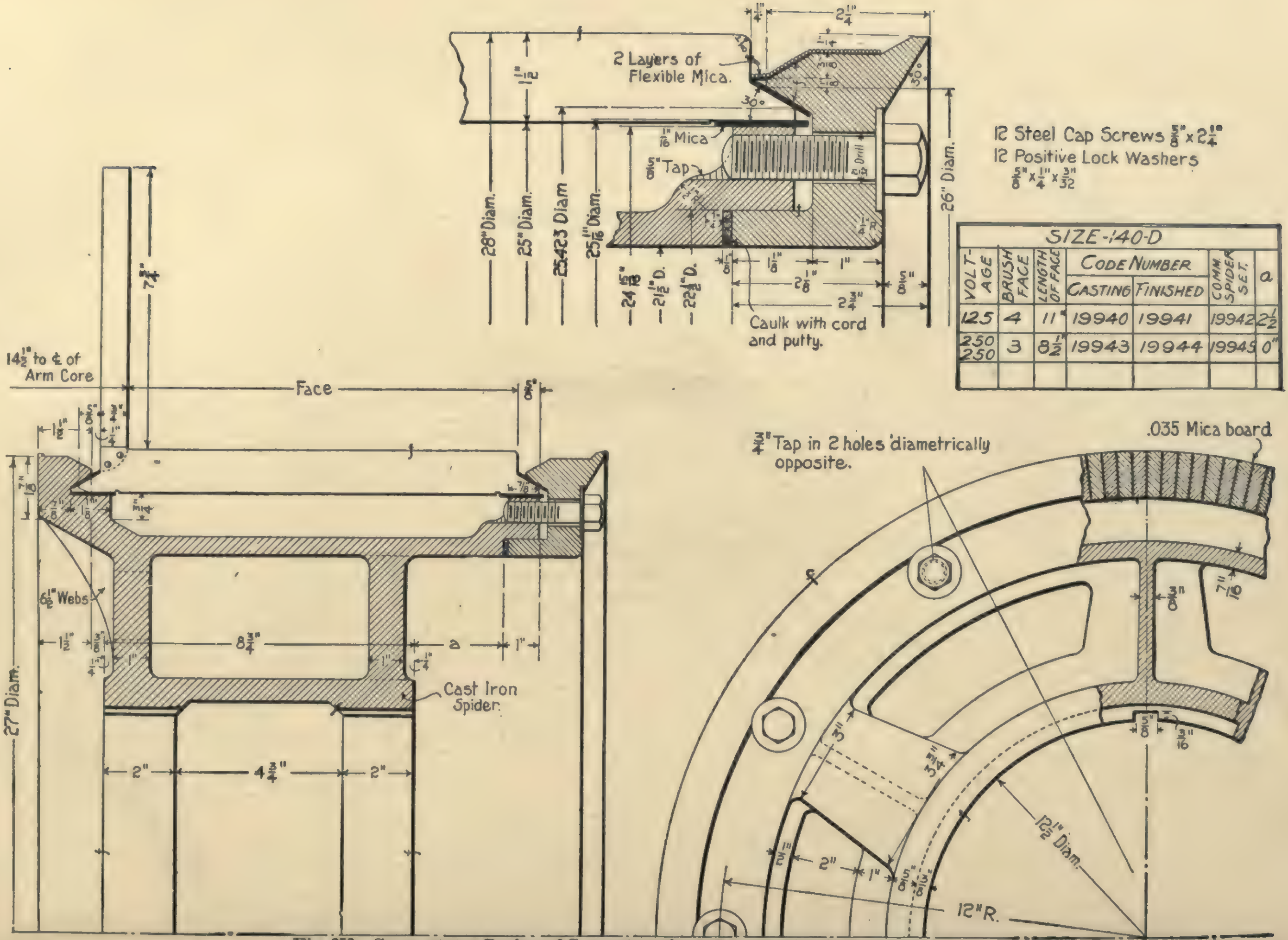
*It is to be noted that for any given output and speed, the product of the diameter by the length of the armature is practically a constant.



SIZE-140-D						
VOLTAGE	BRUSH FACE	LENGTH OF FACE	CODE NUMBER		COMM. SPIDER SET.	a
			CASTING	FINISHED		
125	4	11"	19940	19941	19942	2$\frac{1}{2}$
250 250	3	8$\frac{1}{2}$"	19943	19944	19945	0"

Fig. 250. Commutator Design of Generator whose Construction is Described in Text.

Assuming, in our case, $\Psi = 0.72$, and $B_g = 46{,}000$, we have:

$$\phi = 46{,}000 \times 45 \times 13 \times 3.1416 \times 0.72 \div 8 = 7{,}600{,}000$$

as the assumed flux entering the armature. The value thus found will require adjustment after Z has been determined, the fundamental equation of dynamo-electric machines being used for this purpose. From page 62, this is:

$$\text{(Average) } E = \frac{Z \times \text{r.p.m.} \times \phi \times p}{60 \times 10^8 \times c}.$$

That is,

$$\phi = \frac{E \times c \times 60 \times 10^8}{Z \times p \times \text{r.p.m.}}.$$

Number of Armature Conductors. Having obtained a trial value for the magnetic flux per pole, we can compute the corresponding Z from the preceding formula, adjusting ϕ and Z until the latter comes out properly for the winding selected (see Table VI, page 112). In our case,

$$Z = \frac{263.5^* \times 8 \times 10^8 \times 60}{225 \times 7{,}600{,}000 \times 8} = 924 \text{ (say 928 as a trial number).}$$

Number of Commutator Segments. This is of course equal to the number of conductors divided by 2, 4, 6, etc., although in all but the smallest modern machines, $K = Z \div 2$. The considerations which fix the number have been discussed on page 122. Hence we have:

$$K = 928 \div 2 = 464 \text{ commutator segments.}$$

Size of Commutator. As a rule it is well to make the diameter of the commutator at least ¾ of that of the armature. For large machines, it should be from 12 inches to 18 inches smaller than the armature. Using this as a trial value, divide the periphery by K, to see whether the width allowed per segment is suitable. This should be about 0.2 to 0.8 inch, inclusive of insulation between segments. The necessary provisional length may be found by assuming that the (carbon) brushes will cover from 3 to 3½ segments, and that about 40 amperes may be collected by each square inch of brush-contact area. A margin should be added to this, the working face (see also page 123). The result so obtained should be checked later when the watts lost in commutator heating have been estimated, by seeing whether the surface of the commutator is sufficiently large to dissipate the heat generated, without undue temperature-rise (see page 126). A commutator ought to have about 0.6 square inch of peripheral surface per watt to be dissipated.

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*Note.—Corrected to provide for lost volts (see pages 72 and 214 and Table XIII, page 130).

Having decided in our case that the commutator shall have about 464 segments, and as each segment plus the necessary insulation cannot be less than about 0.2 inch wide at the face of the armature, the periphery of the commutator must be at least 464 × 0.2 = 92.8 inches long. That is, the diameter should be about $92.8 \div \pi = 29.5$ inches.

Allowing 40 amperes per square inch of brush contact, and assuming that a brush covers 3 segments, we have for the net length of the commutator (parallel to the shaft):

$$l_{\text{com}} = \frac{150}{3 \times 0.2 \times 40} = 6.25 \text{ in.},$$

each brush set collecting 150 amperes, as there are 4 pairs of brush sets and the total current output of the machine at rated load is 600 amperes. Adding to the length thus obtained ⅓ as a margin, we have as the length of the commutator:

$$6.25\,(1 + 0.33) = 8.3 \text{ inches (say } 8\tfrac{1}{4} \text{ inches).}$$

Commutator Brushes. Allowing 40 amperes per square inch of brush contact, the area of all the positive (or negative) brushes = 15 sq. in.—*i.e.*, 3¾ sq. in. per set. Let us have 3 brushes 3 inches long, 2½ inches wide, and ½ inch thick per set. From the curve of Fig. 141, page 124, brush-contact drop = 1.5 volts.

Style of Armature Winding. We must now settle upon the type of armature winding to be employed. Modern practice tends toward preserving the utmost simplicity, that is to say, it favors the lap-wound drum executed as a barrel winding so as to have ample cooling surface, the conductors being in two layers so as to take advantage of form winding, and placing two, four, six, or eight conductors in each slot.

Choosing in our case a simplex, singly re-entrant, lap-wound drum winding, the maximum winding pitch will be $y_f = 115$; $y_b = -113$, since we must span about ⅛ of the periphery, there being eight poles (compare page 112, Table VI). As we have assumed a pole span of about 0.75, the minimum values would be about $y_f = 87$; $y_b = -85$. Assuming that the conductors are placed 8 in each slot, there will be about 14 slots to the pole-pitch, requiring the coils to span 14 teeth if we select the largest possible value of the winding-pitch, and 10 teeth if we select the smallest value. Suppose, therefore, that we span over 13 teeth, in which case we shall have $y_t = 107$; $y_b = -105$.

Apportionment of Losses and Checking Size of Armature. We must apportion the losses in order to check up our previous computations in regard to permissible heating limits. Assuming an efficiency of 92 per cent (Table XII), we may allow 2.2 per cent for armature copper loss, 1.6 per cent for armature iron loss, 2.75 per cent for excitation loss, 1.05 per cent for commutator loss, and 0.4 per cent for friction loss, as suggested by the above-mentioned table. The periphery of the armature being $45 \times \pi = 141.4$ inches, and the length over conductors being 27 inches,* the total cylindrical radiating surface will be $141.4 \times 27 = 3{,}820$ square inches; and as the total armature losses are assumed to be 1.6 per cent + 2.2 per cent = 3.8 per cent, or $0.038 \times \frac{150{,}000}{0.92} = 6{,}200$ watts, the peripheral surface will have to dissipate $6{,}200 \div 3{,}820 = 1.63$ watts per square inch. As the peripheral speed is assumed to be 2,650 feet per minute, we see from curve *cc*, Fig. 139 (page 121), that the probable temperature-rise will be $26° \times 1.63 = 42.5°$ C., which will not be too high, since 50° C. rise is permitted by the Standardization Rules of the American Institute of Electrical Engineers. A useful and fairly accurate empirical rule states that the exposed surface of the armature should not be less than 24 square inches for each kilowatt of output. Hence we should need $24 \times 150 = 3{,}600$ square inches. As the armature has 3,820 square inches, there should be ample surface.

Number and Dimensions of the Slots. We may now settle upon the number and dimensions of the slots. The former depends upon the type of winding used, and upon the number of commutator segments. It is almost universal practice to wind all but small armatures with copper strip, the current-density varying from 2,000 to 3,000 amperes per square inch. Assuming, in our case 2,700 amperes per square inch, we require a conductor $\frac{600}{8} \div 2{,}700 = 0.0278$ square inch in cross-section (say 0.028 square inch). As we have decided to place the conductors 8 in a slot (page 202), the total

---

* Assuming length over conductor of barrel-wound armatures to equal twice length over core.

TABLE XIX

Number and Sizes of Armature Slots and Teeth

Diameter of Armature (in inches)	Number of Slots or Teeth	Depth of Slots or Teeth (in inches)
10	25 to 75	0.40 to 1.70
20	50 to 135	0.60 to 1.80
30	75 to 190	0.80 to 1.90
40	95 to 240	1.00 to 2.00
50	110 to 280	1.10 to 2.05
60	125 to 320	1.20 to 2.10
80	150 to 400	1.30 to 2.20
100	175 to 450	1.35 to 2.25
120	190 to 500	1.40 to 2.30
140	200 to 540	1.45 to 2.35
160	210 to 580	1.50 to 2.40

$$\text{Ratio } \frac{\text{Depth of slots}}{\text{Width of slots}}, \text{ from 1.5 to 4}$$

$$\text{Ratio } \frac{\text{Width of slot}}{\text{Width of tooth}}, \text{ from 0.75 to 1.5}$$

copper section per slot will be 8 × 0.028 = 0.224 square inch. Assuming a space-factor (page 88) of, say, 0.34, we have as the area of the solt, 0.224 ÷ 0.34 = 0.66 square inch, nearly. As there will be 928 ÷ 8 = 116 slots (which is within the limits set by Table XIX), and an equal number of teeth in a total perimeter of 141.4 inches, the width of a slot and a tooth at the face of the armature cannot exceed 141.4 ÷ 116 = 1.22 inches. Making the ratio $\frac{\text{Width of slot}}{\text{Width of tooth}} = 1.18$, we have the width of a tooth =

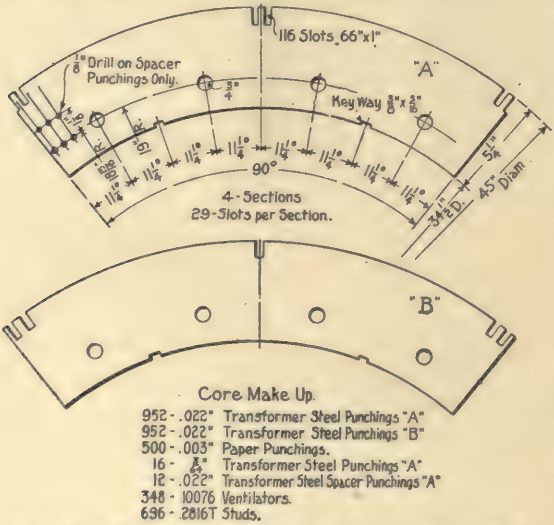

116 Slots .66"x1"
$\frac{1}{8}$" Drill on Spacer Punchings Only.
"A"
$\frac{3}{4}$"
Key Way $\frac{3}{8}$"x$\frac{3}{16}$"
19" R.
$18\frac{15}{16}$" R.
$11\frac{1}{4}$°
90°
4-Sections
29-Slots per Section.
$5\frac{1}{4}$"
45" Diam.
$34\frac{1}{2}$" D.
"B"
Core Make Up.
952 - .022" Transformer Steel Punchings "A"
952 - .022" Transformer Steel Punchings "B"
500 - .003" Paper Punchings.
16 - $\frac{3}{64}$" Transformer Steel Punchings "A"
12 - .022" Transformer Steel Spacer Punchings "A"
348 - 10076 Ventilators.
696 - 2816T Studs.

Fig. 251. Lamination Stamping of Armature whose Construction is Described in Text.

$\frac{1.22^*}{1 + 1.18,} = 0.56$ inch, so that the width of a slot is $1.22 - 0.56 = 0.66$ inch. Hence the depth of the slot will be 0.66 sq. in. ÷ 0.66 in. = 1 inch. These values for the sizes of slots and teeth are seen to lie within the limits suggested by Table XIX.

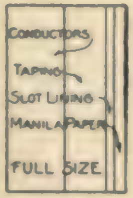


Fig. 252. Section of Part of an Armature Slot.

An enlarged drawing of the slot, showing to scale the arrangements of conductors, is now made (Fig. 252). Each conductor is wrapped with tape to a thickness of 30 mils on each side, and allowing a slot insulation at each side of, say, 24 mils of press-board (two thicknesses, and a wrapping for four conductors of manila 25 mils thick), each conductor must be 80 mils wide, which leaves a clearance of 2 mils. The depth of conductor will be 0.028 ÷ 0.080 = 0.35 inch, or 350 mils. Allow, say, 12 mils of press-board between the upper and lower layers, and 60 mils between the lower layer and the bottom of the slot. We may then account for the contents of a slot as follows:

WIDTH

4 Conductors side by side, bare	4 x 0.080 =	0.320 inch
8 Thicknesses of taping	8 x 0.030 =	0.240 "
2 Thicknesses of slot lining	2 x 0.024 =	0.048 "
2 Thicknesses of manila	2 x 0.025 =	0.050 "
Total		0.558 inch

DEPTH

2 Conductors deep	2 x 0.350 =	0.700 inch
4 Thicknesses of tape	4 x 0.030 =	0.120 "
4 Thicknesses of manila paper	4 x 0.025 =	0.100 "
6 Thicknesses of lining	6 x 0.012 =	0.072 "
Total		0.992 inch

Now, the length of one armature turn (found by drawing the winding to scale and then measuring it), is 87.5 inches; and as the resistance of a copper conductor whose area of cross-section is one square inch, and whose length is 1 foot, at 50° C., is 0.000009088 ohm, we have as the total resistance of the armature winding at 50°C.:

$$r_a = \frac{0.000009088 \times 87.5 \times 464}{64 \times 0.028 \times 12} = 0.0172 \text{ ohm.}$$

Internal Diameter of Core. The internal diameter of the core

---

*Or let x = Width of slot; y = Width of tooth. Then $x + y = 1.22$, and $\frac{x}{y} = 1.18$ Hence $x = 1.18\,y$; and we have $y + 1.18\,y = 1.22$, or $y = \frac{1.12}{1 + 1.18}$.

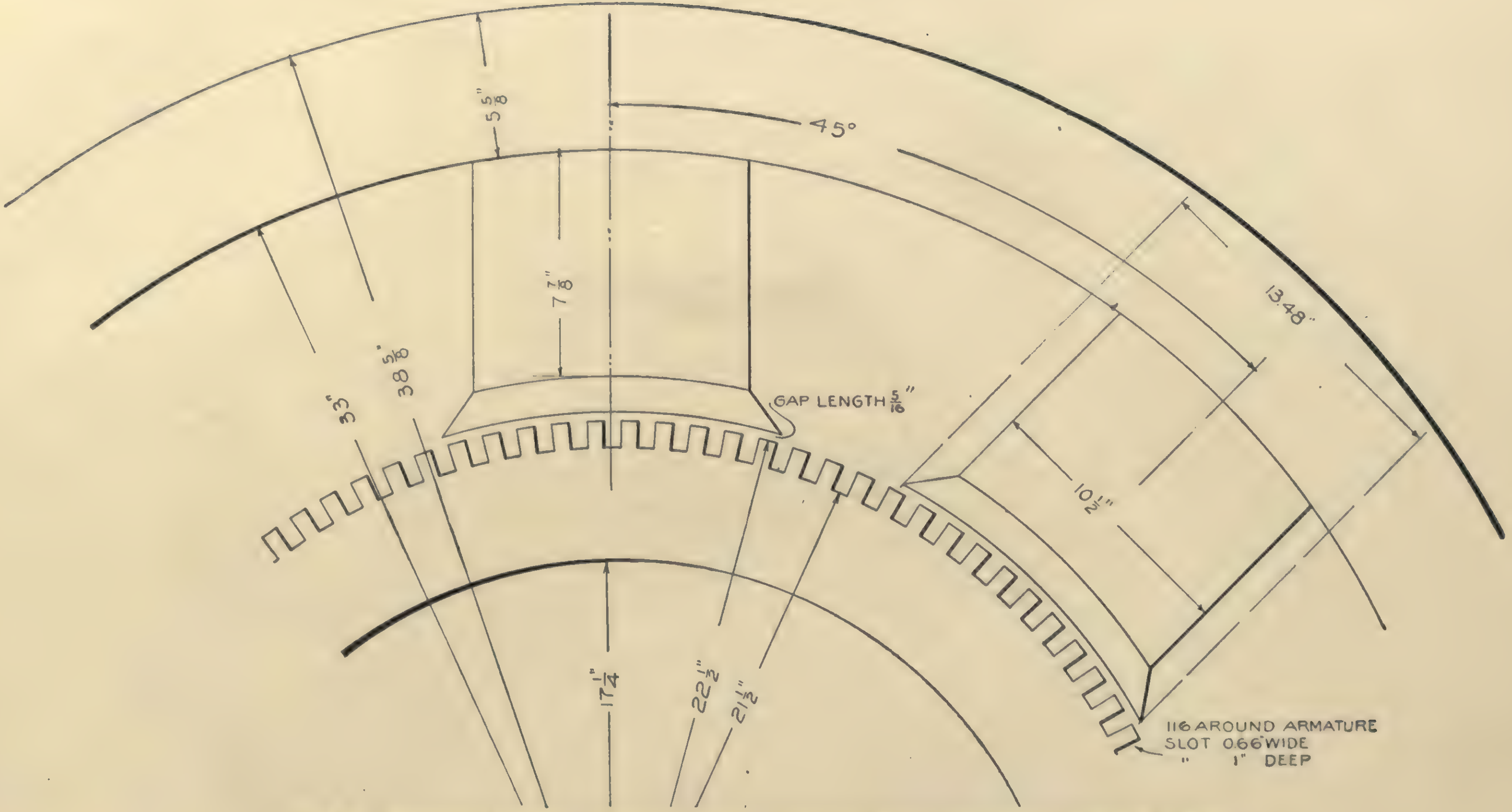
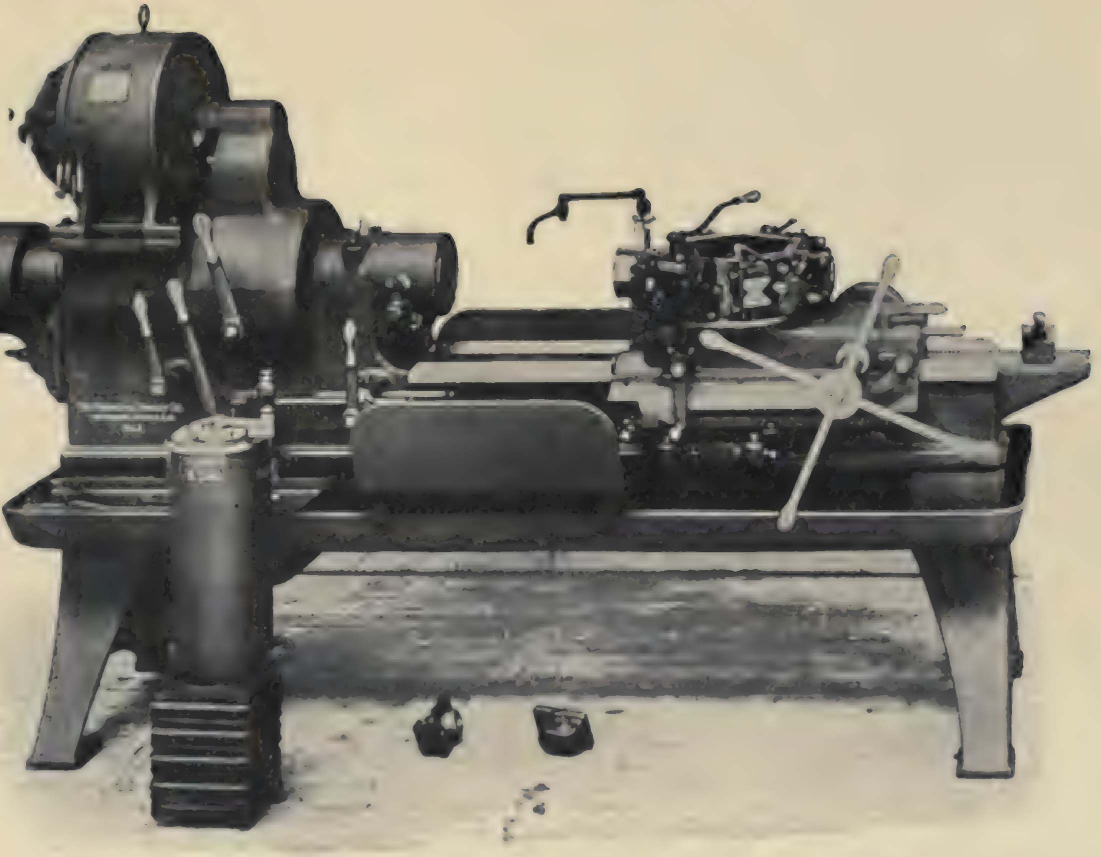


Fig. 253. Dimensioned Diagram of Magnetic Circuit of Generator whose Construction is Described in Text.



WARNER AND SWASEY TURRET LATHE WITH BALANCED THREE-WIRE EQUIPMENT.

Controller within Easy Reach of Operator.

TABLE XX

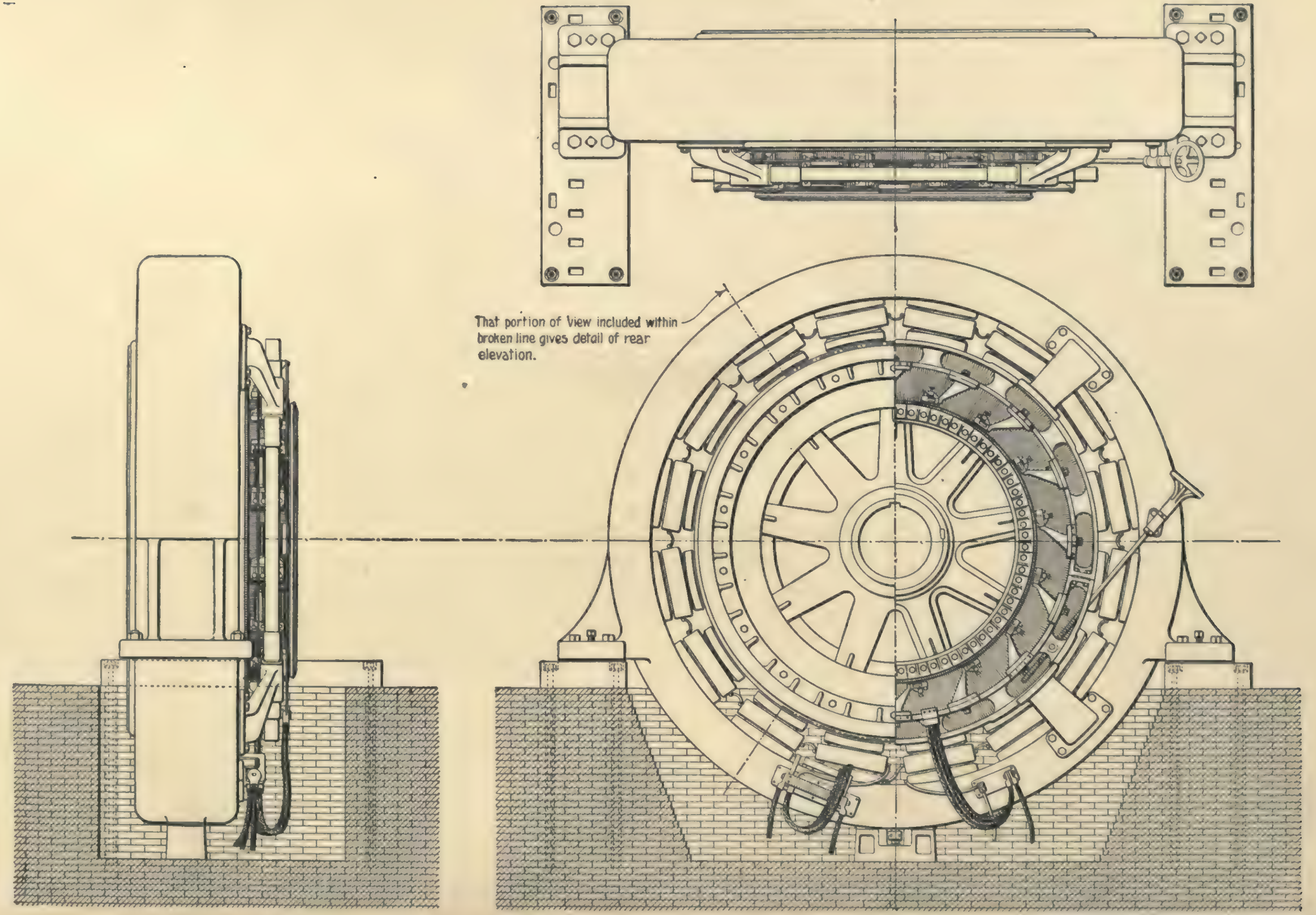
Flux-Densities in Armature Cores

Type	Flux-Density (in lines per sq. in.)
Bipolar drum-core	50,000 to 90,000
Bipolar ring-core	65,000 to 95,000
High-speed multipolar ring-core	45,000 to 85,000
Slow-speed multipolar ring-core	65,000 to 97,000

may now be fixed by ascertaining the requisite radial depth of the core to give an adequate cross-section of iron below the teeth. The final value of this depends upon the permissible iron-loss, which limits the flux-density possible. Table XX gives values for average flux-densities in armature cores; and as our design contemplates a slow-speed multipolar ring-core armature, we may select a flux-density of, say, 83,000 lines per square inch.

Now, the flux through the armature core at rated load is $\frac{1}{2}\ \phi = \frac{7{,}600{,}000}{2} = 3{,}800{,}000$, so that the area of cross-section of the armature core will be $3{,}000{,}000 \div 83{,}000 = 45.8$ square inches. The total length of the armature core over laminations being 13 inches, we have the net length $13 \times 0.814 = 10.575$ inches, allowing 10 per cent of the gross length for insulation between the sheets (page 79), and 1.125 inches for 3 ventilating slots, each $\frac{3}{8}$ inch wide. Hence the radial depth of the armature will be $45.8 \div 10.575 = 4.35$ inches—say $4\frac{1}{4}$ inches. The internal diameter of the armature is therefore $45 - (2 \times 4.25 + 2 \times 1) = 34.5$ inches.

Dimensions of Air-Gap. In assigning a length to the air-gap, it should be borne in mind that this portion of the magnetic circuit of continuous-current machines is not a mere clearance, as in some alternating-current motors. It plays a definite part in the process of commutation. It has been found by experience that a long air-gap, though it necessitates more ampere-turns upon the field-magnets, is of advantage in commutation, as it offers an obstacle to the distortion of the useful flux by the reacting ampere-turns of the armature. Similar results ensue by making the flux-density in the armature teeth high; and it is found that the sum of the ampere-turns required for the air-gap and armature teeth per pole must bear a certain proportion to the number of ampere-turns of the armature under one pole-face at rated load.


That portion of View included within broken line gives detail of rear elevation.

Elevations and Plan of 600 K. W. Railway Generator, 550 Volts. Crocker-Wheeler Company.

Now, since the ampere-turns needful for the air-gap are proportional to the length of the gap l_g and the flux-density in the gap B_g, the following simple approximate rule for the requisite gap-length can be given, assuming that the ampere-turns needful for the teeth bear some definite proportion to those needful for the gap—for instance, that they are equal to 25 per cent of the latter at rated load:

$$l_g = k_4 \times \frac{q\ d}{p\ B_g},$$

where k_4, the stiffness coefficient, varies from about 4 to 8.5 (the lower value applying to cases where the saturation of the teeth exceeds 130,000 lines per square inch); d = diameter of armature; q = number of ampere-conductors per inch of periphery of armature; and p = number of poles. Making $k_4 = 5$, in our design, we have:

$$l_g = 5 \times \frac{\frac{928 \times 75}{141.8} \times 45}{8 \times 46{,}000} = 0.302 \text{ inch (say } \tfrac{5}{16} \text{ inch).}$$

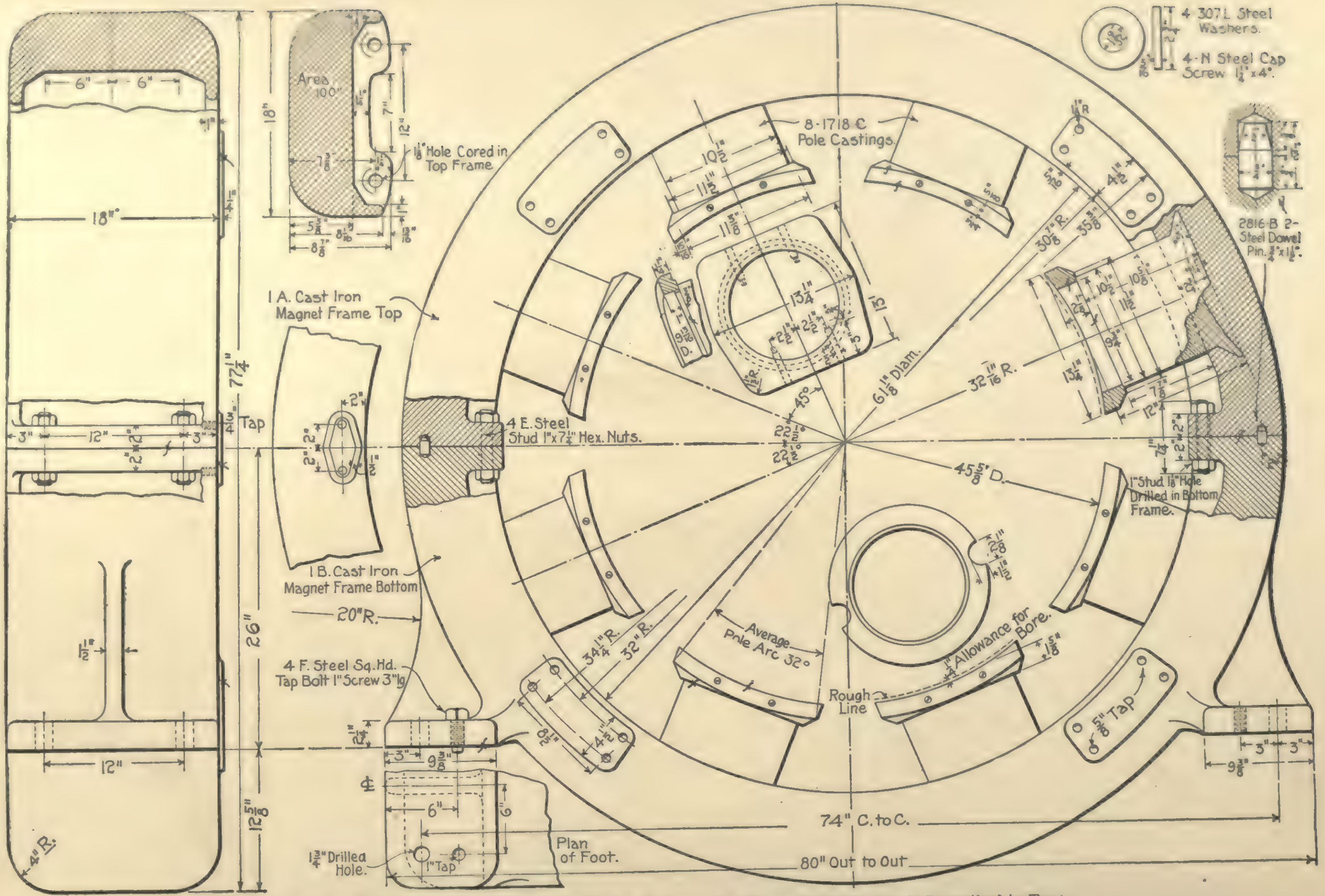
The flux-density in the air-gap, we obtain from Table XXI.

TABLE XXI

Approximate Values of Density in Air-Gap with Multipolar Machines Having Slotted Armatures

Output of Machine (in kilowatts)	Density in Air-Gap (in lines per sq. in.)
1	30,000
5	35,000
10	37,500
25	40,000
50	42,500
100	45,000
200	47,500
300	50,000
500	53,000
1,000	56,000
2,000	59,000

Dimensions of Magnet-Pole Cores. These must have sufficient cross-section to carry the flux required at rated load, including that which forms by leakage—the stray flux. The densities in this portion vary from 75,000 to 100,000 lines per square inch (Table IV, page 90), and the usual leakage coefficients are given in Table II, (page 77). The length of the core must be sufficient to carry the field-exciting winding; and, as a trial value, we may take this equal



4-307L Steel Washers.
4-N Steel Cap Screw 1¼"x4".
2816-B 2-Steel Dowel Pin. ¾"x1½".
8-1718 C Pole Castings.
Area 100"
1⅛" Hole Cored in Top Frame
1 A. Cast Iron Magnet Frame Top
4 E. Steel Stud 1"x7½" Hex. Nuts.
1"Stud 1⅛" Hole Drilled in Bottom Frame.
1 B. Cast Iron Magnet Frame Bottom
20"R.
4 F. Steel Sq. Hd. Tap Bolt 1"Screw 3"lg.
61⅛" Diam.
32 1/16" R.
45⅝" D.
30⅞" R.
35⅜"
34¼" R.
32" R.
Average Pole Arc 32°
¼" Allowance for Bore.
Rough Line
⅝" Tap
74" C. to C.
80" Out to Out
Plan of Foot.
1¾" Drilled Hole.
1" Tap
77¼"
26"
12 5/16"
18"
¾" Tap
4"R.
45°
22½°

Fig. 254. Details of Magnet-Frame and Poles of Generator whose Construction is Described in Text.

to from ¾ to 1 time the diameter (if the core is cylindrical), reducing the value so assumed, if necessary, later on. In case the core is not cylindrical, we may take the length of the pole-core as 20 times the length of the air-gap, if the machine is shunt-wound, and 40 times the length should it be compound-wound.

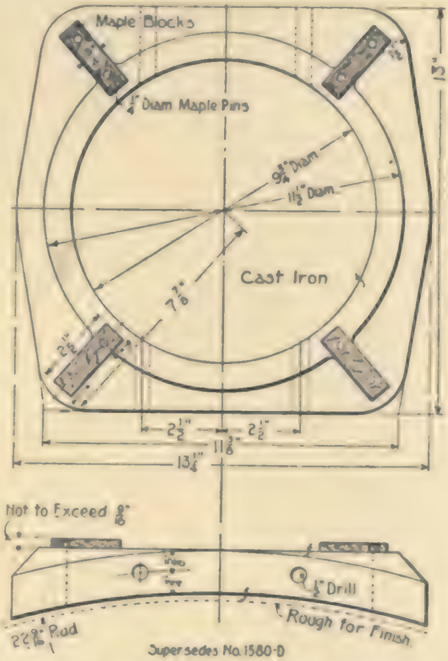


Fig. 255. Make-Up of Pole-Shoe of Generator whose Construction is Described in Text.

In our case, the total flux entering the armature at rated load was assumed to be 7,600,000 lines; and if we assume a leakage coefficient of 1.09, the total flux in the pole-cores will be 7,600,000 × 1.09 = 8,300,000 lines at rated load. Assuming a flux-density in the pole-cores of 96,000 lines per square inch, we have 8,300,000 ÷ 96,000 = 86.5 squae rinches as the area of cross-section of a pole-core. Making them circular in cross-section, we have $2\sqrt{86.5 \div \pi} = 10.5$ inches, as the diameter of the pole-cores. Making the radial length of the cores ¾ the diameter, we get ¾ × 10.5 = 7⅞ inches, as a trial value.

Cross-Section of the Yoke. We may now decide upon the requisite area of cross-section of the yoke, this being fixed when we know the flux-density and the total flux. The latter is 8,300,000 ÷ 2 = 4,150,000 (see page 79); while, if we make the yoke of cast iron, the flux-density should be about 41,000 (Table III); 4,150,000 ÷ 41,000 = 101 sq. in. (say 100 square inches), making a flux-density of 41,500 lines per square inch.

Preliminary Summary. We may now collect and tabulate the values thus far obtained, as follows:

GENERAL SPECIFICATIONS:

Rated load, kilowatts	150
Rated load, terminal volts	250
Rated load, amperes	600
Armature, r. p. m	225
Peripheral speed of armature, in ft. per minute	2,650
Number of poles	8

ARMATURE:

Core-discs, external diameter, in inches	45
“ “ internal “ “ “	34.5
Length of core over laminations, in inches	13
Number of slots	116
Depth of slots, in inches	1
Width of slots, in inches	0.66
Pitch of slots at armature face, in inches	1.22
Depth of iron in core under teeth, in inches	4.25
Number of conductors	928
Arrangement	8 per slot
Style of winding	Simplex parallel
Dimensions of each conductor, in inches	0.08 by 0.35
“ “ “ “ , insulated	0.14 by 0.41
Section of each conductor in square inches	0.016
Winding pitch in number of teeth	13
Length of armature over all, in inches	27

COMMUTATOR:

Diameter, in inches	29.5
Number of segments	464
Length, in inches	8.25
Width of segment at face, in inches	0.16
Thickness of mica insulation	0.04

FIELD-MAGNET:

Outer diameter of yoke, in inches	77.25
Inside diameter of yoke, in inches	66.0
Breadth of yoke, in inches	18.0

All the preliminary computations have now been made, and it now remains to proceed with the final calculations. A scale drawing (similar to Fig. 254) should now be made of the machine, using the trial values thus far found. From this, the designer will be able to judge of the ultimate dimensions of the machine, and, with its aid, he will be able to make a complete set of calculations in accordance with the principles of the preceding pages, for excitation, heating, sparking, and efficiency, as will presently be done. From the results of such calculations, it is then easy to see in what manner to alter the original design in order to fulfil the required conditions.

Excitation. We shall first construct the magnetization curve of the machine by the method described on page 135. We have:

$$E = \frac{Z \times p \times \text{r. p. m.} \times \phi_a}{60 \times 10^8 \times c}.$$

$$= \frac{928 \times 225 \times 8}{60 \times 10^8 \times 8} \phi_a,$$

$$= 0.0000348 \ \phi_a$$

With the aid of this equation, we may compute the following table, the leakage coefficient of the machine being 1.09, by actual measurement:

Generated E. M. F.	Flux Entering Armature per Pole (ϕ_a)	Flux per Pole in Magnet Cores ($\phi_a \times 1.09$)
180	5,180,000	5,650,000
200	5,750,000	6,260,000
220	6,320,000	6,890,000
240	6,900,000	7,520,000
260	7,470,000	8,150,000
280	8,050,000	8,780,000
300	8,620,000	9,400,000
330	9,490,000	10,320,000
360	10,340,000	11,290,000

From the drawings, Figs. 253 and 254, we obtain the following dimensions:

Mean length of magnetic path in magnet-yoke, in inches	29
" " " " " " two magnet-cores, in inches	15.75
" " " " " " armature core, in inches	10
" " " " " " two teeth, in inches	2
" " " " " " two air-gaps, in inches	0.625
Magnetic area of magnet-yoke, in square inches	100
" " " magnet-cores, " " "	86.5
" " " armature core, " " "	45.6

The polar angle being 32°, we have the number of teeth under each pole $\frac{32°}{360°} \times 116 = 10.3$ (say 11 teeth), with the allowance for fringing.

The area of the teeth under each pole may then be taken as $11 \times 0.505 \times 10.72 = 59.5$ square inches.

The area (effective) of the air-gap, being equal to the area of the pole-face, is 163 square inches.

We now have all the data for constructing the magnetization curve of the machine; and in the accompanying table (top of pages 214

Computation of Ampere-Turns

PORTION OF MAGNETIC CIRCUIT	MATERIAL	MEAN LENGTH OF MAGNETIC PATH (Inches)	MAGNETIC AREA (Square Inches)	$E = 180$ $\phi_a = 5{,}180{,}000$ $\phi_m = 5{,}650{,}000$			$E = 200$ $\phi_a = 5{,}750{,}000$ $\phi_m = 6{,}260{,}000$		
				Flux-Density	Ampere-Turns per Inch Length	Ampere-Turns	Flux-Density	Ampere-Turns per Inch Length	Ampere-Turns
Magnet-Yoke.........	Cast Iron	29	2×100	28,250	24	695	31,300	28	812
Two Magnet-Cores...	Cast Steel	15.75	86.5	65,400	5	79	72,500	15	236
Two Air-Gaps........	Air	0.625	163	31,800	9,960	6,230	35,300	11,020	6,900
Two Teeth............	Sheet Steel	2	59.5	87,000	23	46	96,600	52.5	105
Armature Core.......	do	10	2×45.6	56,700	2.5	25	63,000	3.8	38
Ampere-turns per pair of poles...............				......	......	7,075	......	......	8,091

and 215), the ampere-turns required for various generated e. m. f.'s have been computed as outlined on pages 135–143.

From the computed data we locate the following points on the scale:

E	AMPERE-TURNS PER PAIR OF POLES
180	7,075
200	8,091
220	9,252
240	10,694
260	12,493
280	14,412
300	16,517
330	20,219
360	24,392

Plotting a curve between these points, we have the magnetization curve of Fig. 256.

Voltage-Drop Compensation. We have seen that the necessary ampere-turns at rated load will be greater than those at no load by an amount depending upon:

1. The value of the IR drop in the armature and the series field-winding.
2. The value of the brush-contact drop.
3. Amount of armature demagnetization.
4. Amount of armature distortion.

The resistance of the armature winding at 50° C. was found to be 0.0172 ohm; and the rated-load current being 607 amperes, the IR drop will be 607 × 0.0172 = 10.5 volts. The current in the

for Various Generated E. M. F.'s

$E = 220$ $\phi_a = 6{,}320{,}000$ $\phi_m = 6{,}890{,}000$			$E = 240$ $\phi_a = 6{,}900{,}000$ $\phi_m = 7{,}530{,}000$			$E = 260$ $\phi_a = 7{,}470{,}000$ $\phi_m = 8{,}150{,}000$			$E = 280$ $\phi_a = 8{,}050{,}000$ $\phi_m = 8{,}780{,}000$			$E = 300$ $\phi_a = 8{,}620{,}000$ $\phi_m = 9{,}400{,}000$		
Flux-Density	Ampere-Turns per Inch Length	Ampere-Turns	Flux-Density	Ampere-Turns per Inch Length	Ampere-Turns	Flux-Density	Ampere-Turns per Inch Length	Ampere-Turns	Flux-Density	Ampere-Turns per Inch Length	Ampere-Turns	Flux-Density	Ampere-Turns per Inch Length	Ampere-Turns
34,150	38	1,100	37,600	46	1,332	40,750	59.5	1,696	43,900	72.5	2,102	47,050	81.5	2,362
79,500	19	300	86,900	25.4	400	94,200	39.5	622	101,500	56	882	108,900	85	1,330
38,800	12,120	7,590	42,400	13,250	8,280	45,900	14,360	8,960	49,400	15,450	9,650	53,000	16,600	10,330
106,200	99	198	11,600	287	574	127,800	524	1,048	135,300	762	1,524	145,000	1,003	2,006
69,300	6.4	64	75,600	10.8	108	81,900	16.5	165	88,200	25.4	254	94,500	43	430
......	......	9,252	......	......	10,694	......	......	12,491	......	......	14,412	......	......	16,517

brushes being 40 amperes per square inch of contact, we have from Fig. 141 the drop due to brush contact = 1.5 volts. Allowing 1.5 volts for drop in the series field-winding, we see that the machine must generate 250 + 13.5 = 263.5 volts at rated load.

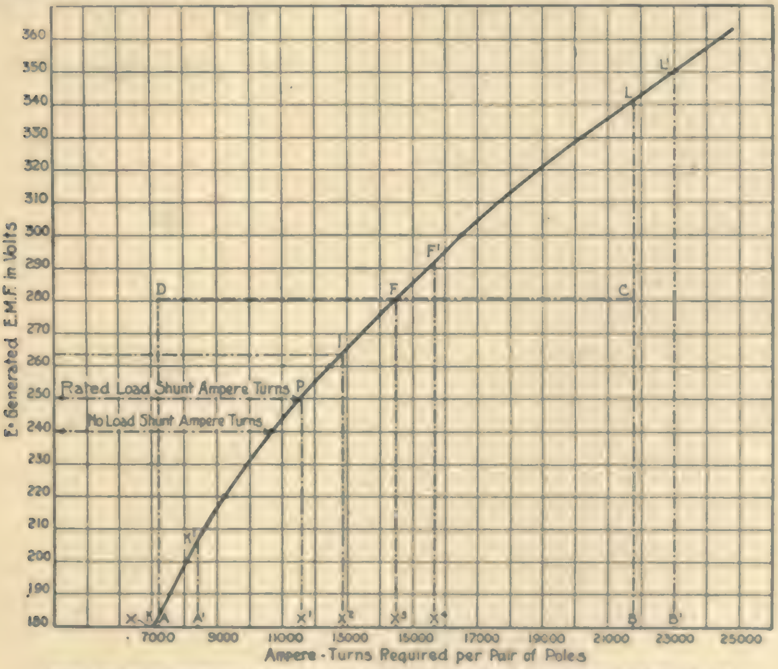


Fig. 256. Magnetization Curve of 150 K. W. 250 Volt Generator, 225 R. P. M.

Finding this point on the scale of ordinates of the curve, Fig. 256, we find the point X_2 on the scale of abscissæ, which corresponds to the ampere-turns required per pair of poles at rated load if armature reaction were entirely absent. This makes $X_2 = 12{,}830$.

At rated load the brushes are given a lead of 5 segments—that is, a lead of 8.6 per cent. Hence the percentage of demagnetizing ampere-turns = 17.2 per cent of the total armature turns. As there are 464 turns on the armature, each carrying 75 amperes, the demagnetizing ampere-turns per pair of poles will be:

$$\frac{460 \times 76 \times .172}{4} = 1{,}510.$$

Multiplying this by the coefficient of magnetic leakage, the compensating ampere-turns per pair of poles will be $1.09 \times 1{,}510 = 1{,}645$.

Adding these to X_2, we find $X_3 = 14{,}470$, assuming, for the moment, that there is no drop in pressure due to diminished permeability of the teeth at the forward pole-horn. For this latter we must allow, as explained on pages 141–144.

We have the distorting ampere-turns per pair of poles $= \frac{464 \times 76 \times 0.828}{4} = 7{,}270$. Therefore set off 7,270 ampere-turns on each side of the point X_3 upon the scale of abscissæ, and thus obtain the points A and B, which represent the hindward and forward pole-horns respectively. If the distortion of the main flux were absent, the latter would be proportional to the area $A\,B\,C\,D$; but as it is not so, it is proportional to the smaller area $ABLK$. In order to make this area equal to that of the rectangle, we must shift the point F higher up the curve to some such position as F', so that area $A'\,B'\,L'\,K'$ = area $A\,B\,C\,D$. In this manner we obtain the point $X_4 = 15{,}700$ as the necessary number of ampere-turns per pair of poles at rated load.

Shunt Field-Winding. From Fig. 256 we see that 10,700 ampere-turns are needed when the terminal voltage of the generator is 240 volts—that is, when no external current is being drawn. Hence we shall require 5,350 ampere-turns per pole.

Assuming a depth of winding of about 1½ inches, we get the length of a mean turn as 3.54 feet. Then, from formula on page 87, we get No. 10 wire as the most suitable size to use. Planning to have

72.5 per cent of the available 250 volts (that is, 181.5 volts) as the terminals of the field spools when hot (the remainder being consumed in the field rheostat), we require $\frac{181.5 \div 8}{2.9} = 6.96$ amperes per spool. Hence the turns per shunt spool will be $\frac{5{,}570}{6.96} = 800$. The length of 800 turns will be 2,830 feet, giving a resistance of very nearly 2.9 ohms per shunt spool. They will be arranged in 25 layers of 32 turns each (2 coils per pole).

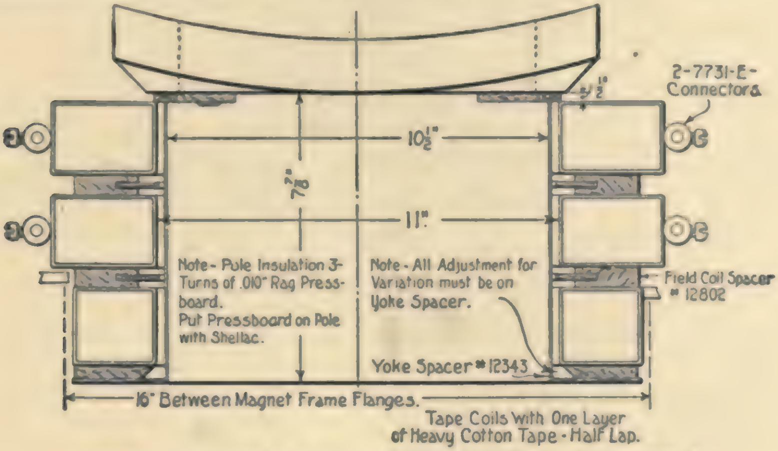

2-7731-E-Connectors
$\frac{1}{2}$"
$10\frac{1}{2}$"
$7\frac{7}{8}$"
11"
Note - Pole Insulation 3-Turns of .010" Rag Pressboard. Put Pressboard on Pole with Shellac.
Note - All Adjustment for Variation must be on Yoke Spacer.
Field Coil Spacer # 12802
Yoke Spacer # 12343
16" Between Magnet Frame Flanges.
Tape Coils with One Layer of Heavy Cotton Tape - Half Lap.

Fig. 257. Make-Up of Field-Coils of Generator whose Construction is Described in Text.

Cumulative Compound Dynamo.

Case	Dimension of Strip.		No. in ‖ in one Coil	No. of Leads.	Depth of Spacers.	Length of Shunt Coil Form.
A	$1\frac{1}{4}$ x .015		1 -	1	$\frac{3}{8}$	$2\frac{1}{8}$
B	$1\frac{1}{4}$ x $\frac{1}{16}$		1 - 3	1	"	$2\frac{1}{8}$
C	$1\frac{1}{4}$ x $\frac{1}{16}$		4 - 8	2	"	$2\frac{1}{8}$
D	$1\frac{1}{2}$ x .015		1 - 8	1	"	2
E	$1\frac{1}{2}$ x $\frac{1}{16}$		1 - 3	1	"	2
F	$1\frac{1}{2}$ x $\frac{1}{16}$		4 - 8	2	"	2.
G	$1\frac{3}{4}$ x .015		1 - 8	1	"	$1\frac{7}{8}$
H	$1\frac{3}{4}$ x $\frac{1}{16}$		1 - 3	1	"	$1\frac{7}{8}$
I	$1\frac{3}{4}$ x $\frac{1}{16}$		4 - 8	2	"	$1\frac{7}{8}$
J	1 x .015		1 - 8	1	"	$1\frac{3}{4}$
K	2 x $\frac{1}{16}$		1 - 3	1	"	$1\frac{3}{4}$
L	2 x $\frac{1}{16}$		4 - 8	2	$\frac{3}{8}$	$1\frac{3}{4}$

Length of Coil 2"

Fig. 258. Table for Make-Up of Field-Coils.

Series Field-Winding. This winding is required to supply 2,280 ampere-turns at a rated load of 607 amperes. Planning to divert 31.6 per cent of this current through a rheostat in parallel with the winding, we find 0.684 × 607 = 415 amperes available for series excitation. Hence each series coil should consist of $\frac{2{,}280}{415} = 5.5$

turns. The mean length of one turn is found to be 3.4 feet, so that 5.5 turns have a length of 18.7 feet.

The series winding per spool consists of 5.5 turns, made up of 5 strips of sheet copper 1.5 inches by $\frac{1}{16}$ inch section = 0.465 square inch. At 20°C. the resistance will therefore be:

$$\frac{0.00000814 \times 18.7}{0.465} = 0.000327 \text{ ohm.}$$

Losses. *Armature.* For the armature copper loss we have:

$$\overline{607}^2 \times 0.0172 = 6{,}350 \text{ watts.}$$

To compute the armature iron loss, we have:

Volume of teeth $= \frac{0.560 + 0.505}{2} \times 1 \times 10.72 \times 116 = 663$ cu. in.

and

Volume of core $= \frac{\pi}{4}\left(\overline{43}^2 - \overline{34.5}^2\right) \times 10.72 = 5{,}555$ cu in.

Hence, from formulæ on pages 14 and 15, we have:

Hysteresis loss in core $= 0.83 \times 0.004 \times 15 \times \overline{83{,}000}^{1.6} \times 5{,}555 \times 10^{-7} =$ 1,970 watts

" " " teeth $= 0.83 \times 0.004 \times 15 \times \overline{126{,}000}^{1.6} \times 663 \times 10^{-7} =$ 477 "

Eddy-current loss in core $= 40.6 \times \overline{0.022}^2 \times \overline{15}^2 \times \overline{83{,}000}^2 \times 5{,}555 \times 10^{-12} =$ 169 "

" " " " teeth $= 40.6 \times \overline{0.022}^2 \times \overline{15}^2 \times \overline{126{,}000}^2 \times 663 \times 10^{-12} =$ 46 "

Total iron losses at rated load = 2,662 watts

Hence, total armature losses = 6,350 + 2,662 = 9,012 watts.

Excitation. The resistance of the shunt field-coils per pole at 50° C. = 2.9 ohms, and they are then supplied with 6.96 amperes. Hence the I^2R loss at rated load $= \overline{6.96}^2 \times 3.22 \times 8 = 1{,}240$ watts. The total loss in shunt field and rheostat at rated load = 250 × 6.96 = 1,740 watts.

The resistance of the series winding of each pole at 50° C. is 0.000365 ohm; so that at rated load, with 415 amperes in this winding, the loss $= \overline{415}^2 \times 0.000365 \times 8 = 490$ watts.

The resistance in parallel with the series winding will be $\frac{415 \times 0.000365 \times 8}{188} = 0.00644$ ohm. Hence the loss in the parallel rheostat at 50° C. and rated load $= \overline{188}^2 \times 0.00644 = 227$ watts.

The total loss in series field-winding and resistance, therefore, = 490 + 227 = 717 watts, giving a drop at rated load of 1.18 volts.

Commutator. Upon the commutator are pressed 24 brushes, each having an area of contact of 1.125 square inches. The total area of all the brushes will therefore be 27 square inches. Hence, by formula on bottom of page 125, assuming a brush tension of 1.25 pounds per square inch, the brush-friction loss = 27 × 1.25 × 0.3 × 1,650 × 746 ÷ 3,300 = 378 watts.

The total brush-contact drop is 1.6 volts. Hence the loss at brush contact = 607 × 1.6 = 971 watts. This makes the total commutator loss = 971 + 378 = 1,249 watts.

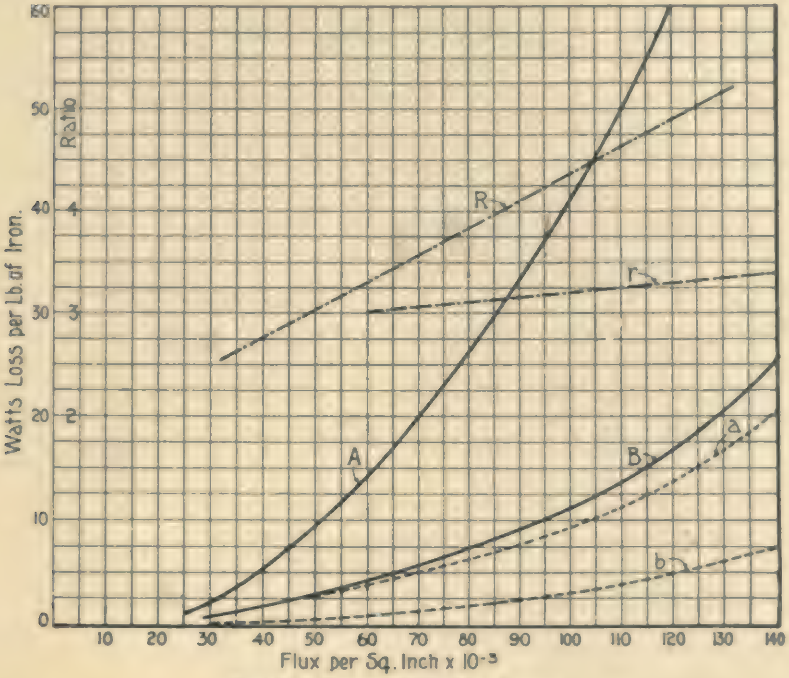


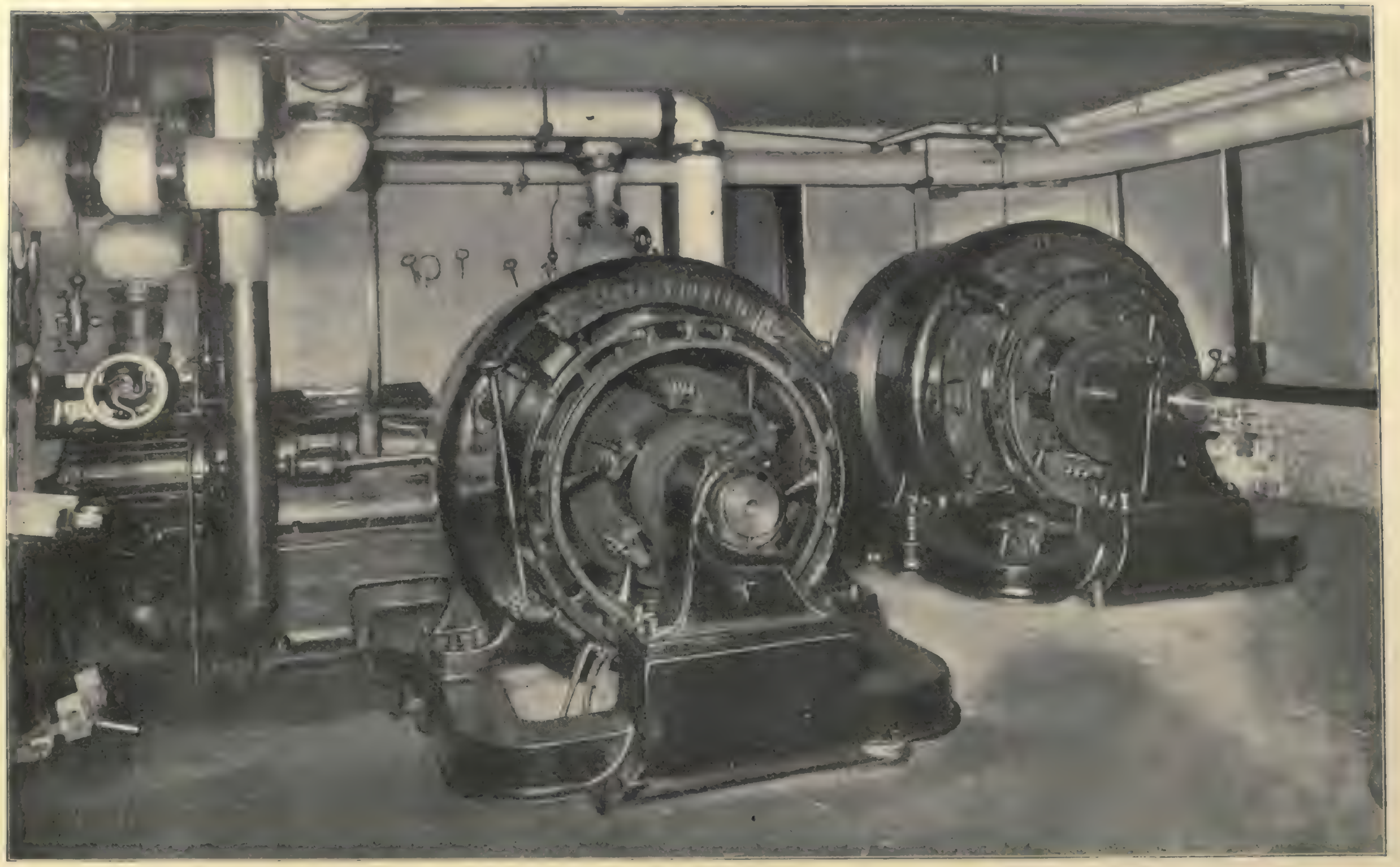
Fig. 259. Curves of Machine Losses.

A—Machine Losses at 30 Cycles per Second; *a*—Sample Losses at 30 Cycles per Second; *R*—Ratio between *a* and *A*; *B*—Machine Losses at 15 Cycles per Second; *b*—Sample Losses at 15 Cycles per Second; *r*—Ratio between *b* and *B*.

Bearing Friction and Windage. Owing to this being a direct-driven (slow-speed) machine, we may assume the losses due to bearing friction and windage as ⅔ of 1 per cent of the output (that is = 1,000 watts).

Efficiency. The total rated-load losses are:

Armature loss	**9,012**	**watts**	**= 5.51**	**per cent**
Excitation loss	2,457	"	= 1.50	" "
Commutator loss	1,249	"	= 0.58	" "
Bearing friction and windage	1,000	"	= 0.61	" "
Total losses	13,718	"	8.20	" "



Crocker-Wheeler Generators of Type Described in Text, Installed in Whitehall Building, New York City.

Hence the efficiency is:

$$\frac{150{,}000}{163{,}440} = 91.8 \text{ per cent.}$$

Heating. (*a*) *Armature.* From the drawings the radiating surface of the armature is found to be 4,510 square inches (counting cylindrical surface, and tails of rear flanges); the peripheral speed is 2,650 feet per minute.

The total armature loss being 9,012 watts, we must radiate $\frac{9{,}012}{4{,}510} = 2$ watts per square inch of radiating surface. Fig. 139 shows that this will give a rise of 50° C. at rated load and speed; but actual tests on the machine have shown an increase (by thermometer) of only 25° C.

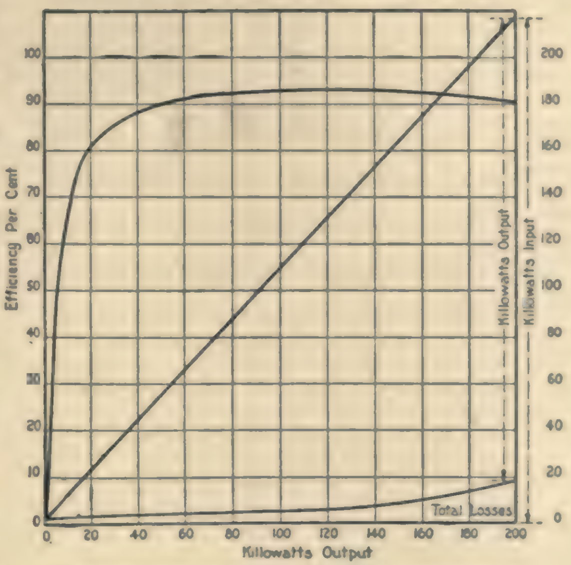


Fig. 260. Efficiency Curve of 140 D Generator, 250 V., 150 KW., 225 R. P. M.

(*b*) *Magnet System.* The total radiating surface provided for the shunt winding = 1,740 square inches, so that it is necessary to radiate 0.715 watt per square inch. Assuming $h = 35$ in formula on page 91, we have:

$$\theta_m = 35 \times 0.715 = 25° \text{ C. for the shunt winding.}$$

Actual test showed it to be 22.5° C.

The total radiating surface allotted to the series-winding = 615 square inches, and as 490 watts are consumed here, we must radiate $\frac{490}{615} = 0.796$ watt per square inch. Therefore,

$$\theta_m = 35 \times 0.796 = 27.8° \text{ C.}$$

Commutator. For the probable testing of this portion of the machine, we have, from page 126:

$$\theta_c = \frac{46.5 \times 971}{1{,}100(1 + 0.005 \times 1{,}650)} = 23° \text{ C.}$$

Sparking. The ratio of the ampere-turns required at full excitation to drive the flux through the air-gap and teeth, to the whole number of ampere conductors (at rated load) that lie under one pole-face, is 5,000 ÷ 3,635 = 1.37, providing a stiff field. The amperes collected per brush set are 150. The voltage between commutator segments is 4.32, and the *stiffness ratio* (page 208) is (46,000 ÷ 928 × 76) × 141.8 = 92*; all of which indicate sparkless commutation.

DETAIL SHEET

GENERATOR DESIGN

Name....................

Date submitted..............

Specification

1	Kilowatts	150
2	Terminal volts, rated load	250
3	Kilowatts no load	240
4	Amperes, rated load	600
5	Revolutions per minute	225
6	Number of poles	8
7	Frequency in cycles per second	15
8	Peripheral speed of armature, feet per minute	2,650

Materials

9	Armature core	Sheet Steel
10	Armature spider	Cast Iron
11	Armature binding wire	No. 16 Phosphor Bronze
12	Conductors	Copper
13	Commutator segments	Copper
14	" leads	Copper
15	" spider	Cast Iron
16	Pole-pieces	Cast Iron
17	Magnet-cores	Cast Steel
18	Magnet-yoke	Cast Iron

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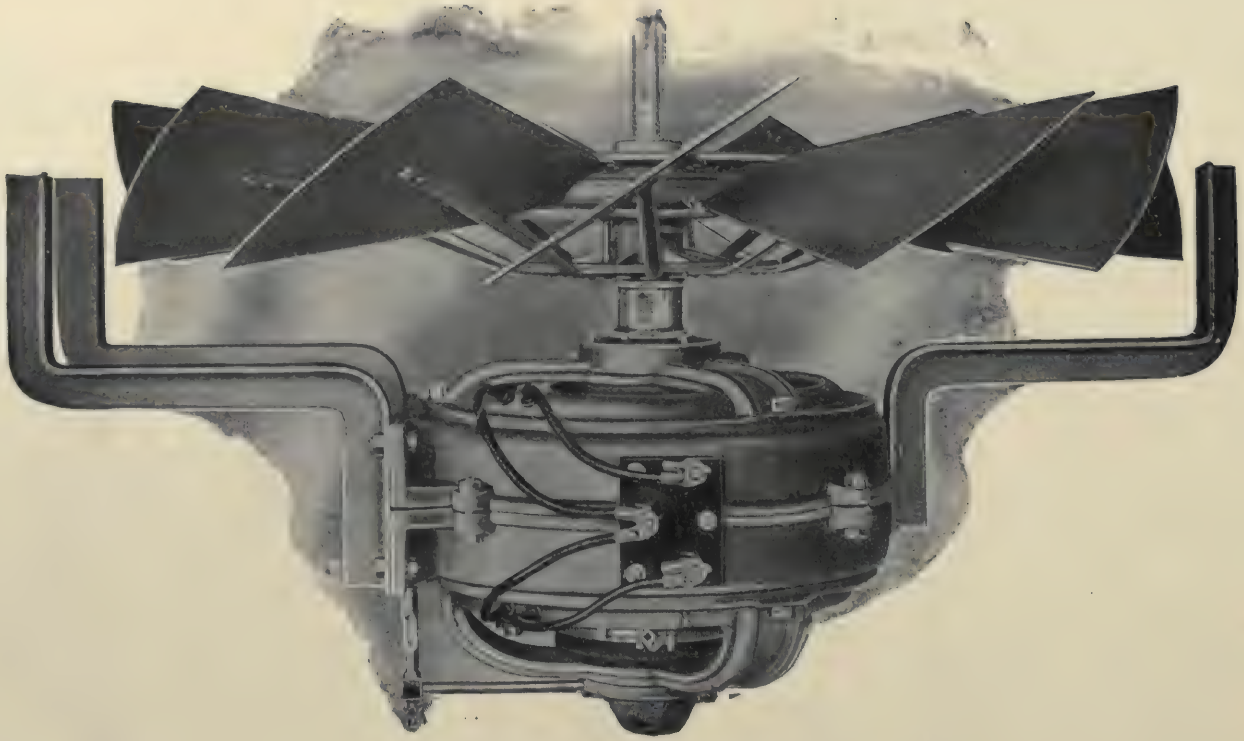
*If $92 < \frac{\text{Stiffness coefficient} \times \text{Diameter of armature}}{p \times \text{Length of air-gap}}$, the conditions as regards air-gap length are correct.



MULTIPOLAR MOTOR DIRECT-CONNECTED TO 60-INCH FAN.

Sprague Electric Company.

19	Brushes	Carbon
20	Shaft	Steel (0.35%C.)
21	Bearings	

DIMENSIONS

Armature—

22	Diameter over all	45 in.
23	Diameter at bottom of slots	43 in.
24	Internal diameter of core	34.5 in.
25	Length over conductors	27 in.
26	Length of core over laminations	13 in.
27	Insulation between sheets %	9.8%
28	Number of ventilating ducts	3
29	Width of each ventilating duct	0.375 in.
30	Effective length, magnetic iron	10.72 in.
31	Effective length of core ÷ total length	82.5%
32	Thickness of sheets	0.022 in. and $\frac{3}{64}$ in. at ends
33	Number of sheets	479 of 0.022 in. and 4 of $\frac{3}{64}$ in.*
34	Number of slots	116
35	Depth of slot	1 in.
36	Width of slot at root	0.66 in.
37	“ “ surface	0.66 in.
38	Width of tooth at root	0.505 in.
39	Width of tooth at armature face	0.560 in.
40	Size of conductor, Diam	Depth . . 0.35 in. Width . . 0.08 in.
41	Size of conductor insulated	0.14 in. by 0.41 in.
42	Pitch of winding, No. of teeth	13
43	Total number of face wires or bars	928
44	Arrang. of wires or bars per slot	4-0.08 in. wide; 2-0.35 in. deep
45	Number in parallel per slot	0
46	“ “ series “ “	8
47	Copper section ÷ slot section	0.34
48	Total insulation between cond. and core	0.079 in. on sides of slots 0.127 in. on bottom do.
49	Thickness insulation between conds.	0.060 in. vertically. 0.110 in. between layers

Gap—

50	Length in center	$\frac{5}{16}$ in.
51	Length maximum	do.
52	Bore of field	45$\frac{3}{8}$ in.

Pole-Piece—

53	Length parallel to shaft	13 in.
54	Length of arc, max	13.48 in.
55	Length of arc, min	11.57 in
56	Thickness at edge of core	1$\frac{3}{8}$ in

---

*4 sections per sheet.

Magnet-Core—

57	Length of magnet-core, radial	$7\frac{7}{8}$ in.
58	Diameter of magnet-core	$10\frac{1}{2}$ in.
59	Length parallel to shaft	$10\frac{1}{2}$ in.
60	Distance between magnet-cores	9 in.

Magnet-Coils—

61	Length over all winding space	$7\frac{7}{8}$ in.
62	Thickness of insulation on flanges	
63	Thickness of insulation on body	$\frac{1}{16}$ in.
64	Length of main winding space, ex. insuln. (shunt)	Each coil = 2 in.
65	Length of compound winding space, ex. insuln.	$1\frac{1}{2}$ in.
66	Depth of winding space, ex. insuln.	
67	Total section of field copper	9.12 sq. in.
68	Size of shunt conductor	No. 10 B. and S.G.
69	Turns in series per pole	2 coils, each 400 turns
70	Size of compound conductor	5 strips, $1\frac{1}{2}$ in. by $\frac{1}{16}$ in., in parallel
71	Turns in series per pole	$5\frac{1}{2}$

Yoke—

72	Outside diameter	$77\frac{1}{4}$ in.
73	Inside diameter	66 in.
74	Thickness	$5\frac{5}{8}$ in.
75	Diameter over ribs	
76	Thickness of ribs	1 in.
77	Length along armature	18 in.

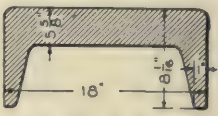


Fig. 261. Section of Yoke.

Commutator and Brushes—

78	Diameter	28 in.
79	Number of segments	464
80	" " per slot	4
81	Width of segment at commutator face	0.158 in.
82	Width of segment at root	0.138 in.
83	Useful depth of segment	1.25 in.
84	Thickness of mica insulation	0.035 in.
85	Available length surface of segment	8.25 in.
86	Cross-section commutator leads	0.0468 sq. in.
87	Total length of commutator	12.5 in.
88	Peripheral speed	1,650 ft. per min.
89	Number of sets of brushes	8
90	Number in one set	3
91	Length	3 in.
92	Width	2.25 in.
93	Thickness	0.50 in.
94	Area of contact, one brush	1.125 sq. in.
95	Area of contact, one set	3.375 sq. in.
96	Type of brush	Radial Carbon

ARMATURE

97	No-load voltage	240 volts
98	Type of winding	Simplex, Singly Re-entrant, Lap-Wound Drum

99	Number of circuits	8
100	Mean length, one armature turn	87.5 in.
101	Total armature turns	464
102	Turns in series between brushes	58
103	Length between brushes	423 ft.
104	Cross-section one arm. conductor	0.028 sq. in.
105	Amperes per square inch in armature conductor	2,714
106	Resistances between brushes at 20° C.	0.123 ohm
107	Resistances between brushes at 50° C.	0.138 ohm
108	Total resistance of armature at	20° C. 0.0154 ohm 50° C. 0.0172 ohm
109	C. R. drop in armature at 50° C.	10.5 volts
110	Total internal voltage, rated load	263.5 volts
111	Amperes per square inch in commutator connections	1,210

COMMUTATOR

112	Average volts between bars	4.32
113	Amperes per square inch of brush contact	45
114	Drop in brush contacts	1 5 volts

COMMUTATION

115	Average voltage between commutator segments	4.32
116	Armature turns per pole	58
117	Amperes per turn	76
118	Armature ampere-turns per pole	4,400
119	Allowable ampere-turns per pole	4,560*
120	Segments lead of brushes, no load	
	half load	
	rated load	5
121	Percentage lead of brushes, rated load	8.6%
122	Percentage demagnetizing ampere-turns, rated load	17.2%
123	Percentage distorting ampere-turns, rated load	82.8%
124	Demagnetizing ampere-turns per pole	755
125	Distorting ampere-turns	3,635

SHUNT OR MAIN FIELD

126	No. of turns in series per pole	2 × 400 = 800
127	No. of coils in series	16 (*i.e.*, 2 per pole)
128	Mean length of turn	42.6 in.
129	Resistance of mean turn 20° C.	0.00362 ohm
130	Total number of turns	6,400
131	Total resistance at 20° C.	23.2 ohms
132	Total resistance at 50° C.	26.1 ohms
133	Amperes, no load	6.675
134	Amperes, rated load	6.96
135	Volts at field terminals, no load	240
136	Volts at field terminals, rated load	250
137	Amperes per sq. in., no load	818

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*Allowable ampere-turns per pole = number of ampere-turns per pole required to maintain the rated-load flux in the air-gap.

138	Amperes per sq. in., rated load	855	
139	Rheostat resistance	24 ohms	
140	C. R. drop rheostat 50° C.	68.5 volts	

SERIES OR COMPOUND FIELD

141	No. of turns in series per coil	5½	
142	No. of coils in series	8	
143	Mean length of turn	40.7 in.	
144	Resistance of mean turn	0.0000585 ohm	
145	Total number of turns	44	
146	Total resistance at 20° C	0.00257 ohm	
147	Total resistance at 50° C	0.00290 ohm	
148	Amperes, rated load	415	
149	Amperes per sq. in., rated load	892	
150	Resistance of rheostat in parallel with series field	0.00644 ohm	

MAGNETIC

151	Megalines entering armature per pole, no load	6.9	
152	Megalines, entering armature per pole, rated load	7.6	
153	Coefficient of magnetic leakage, actual	1.09	
154	Megalines in field, no load	7.5	
155	Megalines in field, rated load	8.3	
156	*Armature*, section	45.6 sq. in.	
157	Length, magnetic	10 in.	
158	Density no load	75,600	
159	“ rated load	83,000	
160	Ampere-turns per inch length, no load	10.8	
161	Ampere-turns per inch length, rated load	18.0	
162	Ampere-turns, no load	108	per pair of poles
163	Ampere-turns, rated load	180	
164	*Teeth* transmitting flux from one pole-piece	$\frac{32^\circ}{360^\circ} \times 116 = 10.3$	
165	Allowances for spread of flux	07	
166	Section of roots	59.5 sq. in.	
167	Length	$2 \times 1 = 2$ in.	
168	Apparent density, no load	116,000	
169	“ “ rated load	127,800	
170	Corrected “ no load	114,000	
171	“ “ rated load	123,000	
172	Ampere-turns per inch length, no load	287	
173	Ampere-turns per inch length, rated load	565	
174	Ampere-turns, no load	574	per pair of poles
175	Ampere-turns, rated load	1,130	
176	*Gap*, section at pole-face	163 sq. in.	
177	Length gap	$2 \times$ 5-16 in. = 0.625 in.	
178	Density at pole-face, no load	42,400	
179	“ “ rated load	46,000	
180	Ampere-turns, no load	8,280	per pair of poles
181	Ampere-turns, rated load	9,090	
182	*Magnet-Core*, section	86.5 sq. in.	
183	Length (magnetic)	$2 \times 7.875 = 15.75$ in.	

184	Density, no load	86,900	
185	Density, rated load	96,000	
186	Ampere-turns per inch length, no load	25.4	
187	Ampere-turns per inch length, rated load	42	
188	Ampere-turns, no load	400	per pair of poles
189	Ampere-turns, rated load	661	
190	*Magnetic Yoke*, section	100 sq. in.	
191	Length per pole	29 in.	
192	Density, no load	37,600	
193	Density, rated load	41,500	
194	Ampere-turns per inch length, no load	46	
195	Ampere-turns per inch length, rated load	61	
196	Ampere-turns, no load	1,332	per pair of poles
197	Ampere-turns, rated load	1,769	

AMPERE-TURNS PER POLE

		No Load and 240 Volts.	Rated Load and 263.5 Internal Volts
198	Armature core	54	90
199	Armature teeth	287	565
200	Gap	4,140	4,545
201 202	Magnet-pole Magnet-core	200	330
203	Magnet-yoke	666	884
		5,347	6,414

204	Demagnetizing ampere-turns per pole, at rated load	755
205	Allowance for increase in density through distortion	615
206	Total ampere-turns at rated load and 250 terminal volts	7,850

207 If the rheostat in the shunt circuit is adjusted to give 5,347 ampere-turns at 240 volts, then, when the terminal voltage is 250, the shunt excitation will amount to $\frac{250}{240} \times 5{,}347 = 5{,}570$ ampere-turns. $7{,}850 - 5{,}570 = 2{,}280$ ampere-turns must be supplied by the series winding.

CALCULATION OF SPOOL WINDING

Shunt—

208	Mean length of one shunt turn =	42.6 in.
209	Ampere-turns per shunt spool at rated load	5,570
210	Ampere feet	19,800
211	Total radiating surface of two shunt field-spools + series field-spool	294 sq. in.
212	Proportion available for shunt = —— × =	217 sq. in.
213	Permit .40 watt per square in, at 20° C.	
214	∴ 217 × .40 = 87 watts per shunt spool at 20° C	
215	And 98 watts per shunt spool at 50° C.	

216 Plan to have 72.5 per cent of the available 250 volts (*i.e.*, 181.5) volts at the terminals of the field-spools when hot, the remainder being consumed in the field rheostat. This is 161.5 volts at 20° C., or

20.2 volts per spool. Hence require $\frac{20.2}{2.9} = 6.96$ amperes per spool.

217 Turns per shunt spool $= \frac{5.570}{6.96} =$ 800

218 Length of 800 turns..................................2,830 ft.

219 Pounds per 1,000 ft..............................40 "calculated"

220 No. 10 B. and S. has 31.5 lbs. per 1,000 ft., 2.83 × 31.5 = 89 lbs. "used" per pole.

221 Bare diameter.......................................0.102 in.

222 S. C. C. diameter...................................0.108 in.

223 Cross-section of copper...........................0.00815 sq. in.

224 Amperes per square inch...................................855

225 Length of the portion of winding space available for shunt winding. 4 in.

226 Winding consists of 25 layers of 32 turns each, of No. 10 B. and S.

SERIES WINDING

227 The series winding is required to supply 2,280 ampere-turns at rated load of 600 amperes.

228 Planning to divert 31.6 per cent through a rheostat in parallel with the series winding, we find we have 607 × 0.684 = 415 amperes available for the series excitation; hence each series coil should consist of $\frac{2,280}{415} = 5.5$ turns.

229 Mean length of series turn..................................40.8 in.

230 Total length of 5.5 turns...................................18.7 ft.

231 Radiating surface available for series coil................77 sq. in.

232 Permit .40 watt per square inch in series winding at 20° C.

233 Watts lost per series spool at 20° C. = .40 × 77 = ...31

234 Hence resistance per spool at 20° C. $= \frac{31}{(415)^2} = 0.00018$ ohm.

235 Copper cross-section = 0.465 square inch, "calculated."

236 Series winding per spool consists of 5.5 turns made up of 5 strips of sheet copper 1.5 in × $\frac{1}{16}$ in.

THERMAL CALCULATIONS AND LOSSES

ARMATURE—

237 I^2R loss, rated load, at 50°C ....6,350 watts

238 Hysteresis loss, rated load { core ....1,970 "
teeth ....477 "

239 Eddy-current loss, rated load { core......................169 "
teeth ....46 "

240 Total hys. and eddy-cur. losses, rated load.............. 2,662 "

241 Total hys. and eddy-cur. losses, no load.................2,300 "

242 Total armature loss, rated load..........................9,012 "

243 Radiating surface of armature........................4,510 sq. in.

244 Watts per square inch radiating surface...........................2

245 Assumed increase of temperature per watt per square inch of radiating surface as measured by increased resistance............ = 25°C.

246 Hence, estimated total increase temperature of armature at rated load.. = 50°C.

SHUNT OR MAIN FIELD—

247	I^2R total, no load 50° C.	939 watts
248	I^2R total, rated load 50° C.	1,240 "
249	Radiating surface	1,740 sq. in.
250	Watts per sq. in., rated load	0.715
251	Total increase in temperature, rated load	25° C.
252	I. E. rated load, field and rheostat	1,740 watts

SERIES OR COMPOUND FIELD—

253	I^2R total, rated load	490 watts
254	Radiating surface	615 sq. in.
255	Watts per sq. in., rated load	0.796
256	Total increase in temperature, rated load	27.8° C.
257	I. E. rated load, field and resistance	717 watts

COMMUTATOR—

258	Area of all positive brushes	13.5 sq. in.
259	Brush-contact loss	971 watts
260	Brush pressure assumed, 1.25 lbs. per square inch	33.8 lbs.
261	Coefficient friction	0.3
262	Peripheral speed of commutator, feet per minute	1,650
263	Brush friction	10.1 lbs.
264	Stray power lost in commutator	378 watts
265	Total commutator loss	1,249 watts
266	Radiating surface in sq. in.	1,100
267	Watts per square inch radiating surface of commutator, rated load	1.14
268	Increase of temperature per watt per sq. in. radiating surface =	20° C.
269	Total estimated increase of tem. of commutator, rated load	22.8° C.

BRUSHES—

270	Total estimated increase of temperature	30° C.
271	**Total losses, rated load**	13,440 watts
272	**Total losses, no load**	4,690 watts

EFFICIENCY CALCULATION

273	Output, rated load	150,000 watts
274	Core loss	2,662 "
275	Commutator and brush losses	1,249 "
276	Armature I^2R at 50° C.	6,350 "
277	Shunt spools I^2R at 50° C.	1,240 "
278	" rheostat at 50° C.	500 "
279	Series spools I^2R at 50° C.	490 "
280	" rheostat at 50° C.	227 "
281	Friction in bearings and windage	1,000 "
	Input	163,718 "
282	Commercial efficiency at rated load and 50° C.	91.7 per cent
283	Inherent regulation, per cent	104 per cent

WEIGHTS

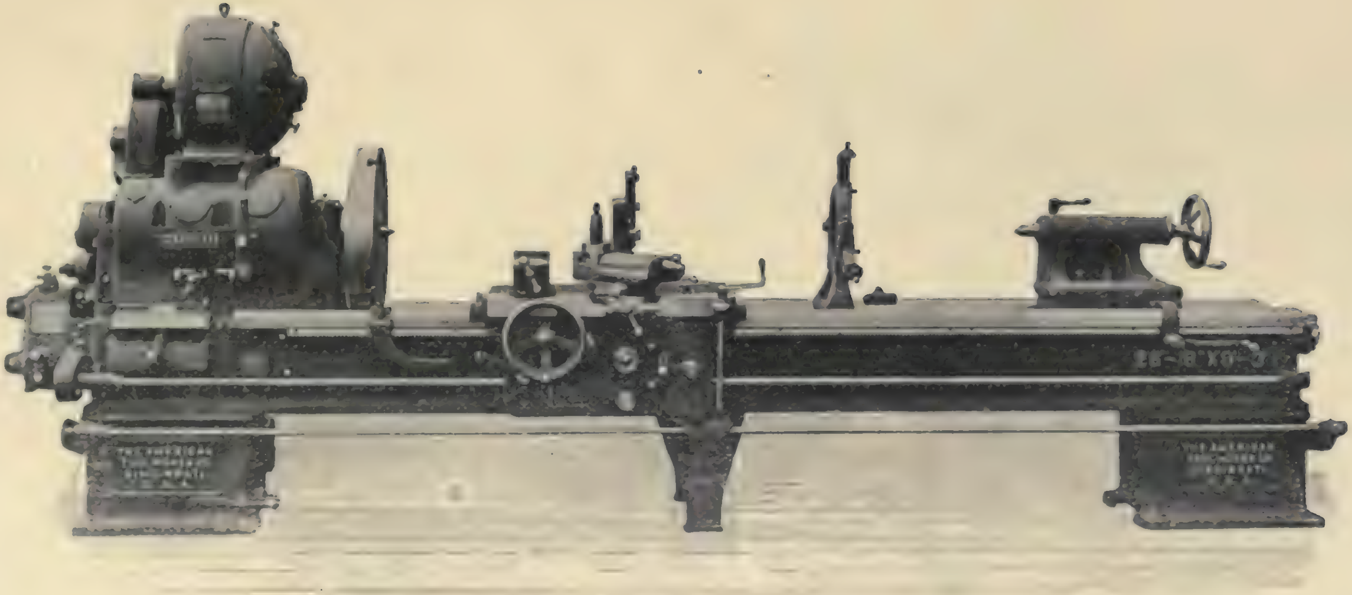
284	Armature magnetic core	1,330 lbs.
285	" teeth	140 "

286	Armature spider	1,000 lbs.
287	" shaft	
288	" end flanges	450 lbs.
289	" copper	450 "
290	Commutator segments	510 "
291	" spider	400 "
292	" rings	90 "
293	Other parts of armature and commutator	80 "
294	Armature complete, including commutator and shaft	4,450 "
295	Pole-pieces	2,509 "
296	Magnet-cores	
297	Magnet-yoke	3,794 "
298	Shunt coils	694 "
299	Series coils	306 "
300	Total spool copper	1,080 "
301	Brush-gear	533 "
302	Bed-plate and bearings	
303	Machine complete	12,400 net lbs.

DRAWINGS REQUIRED

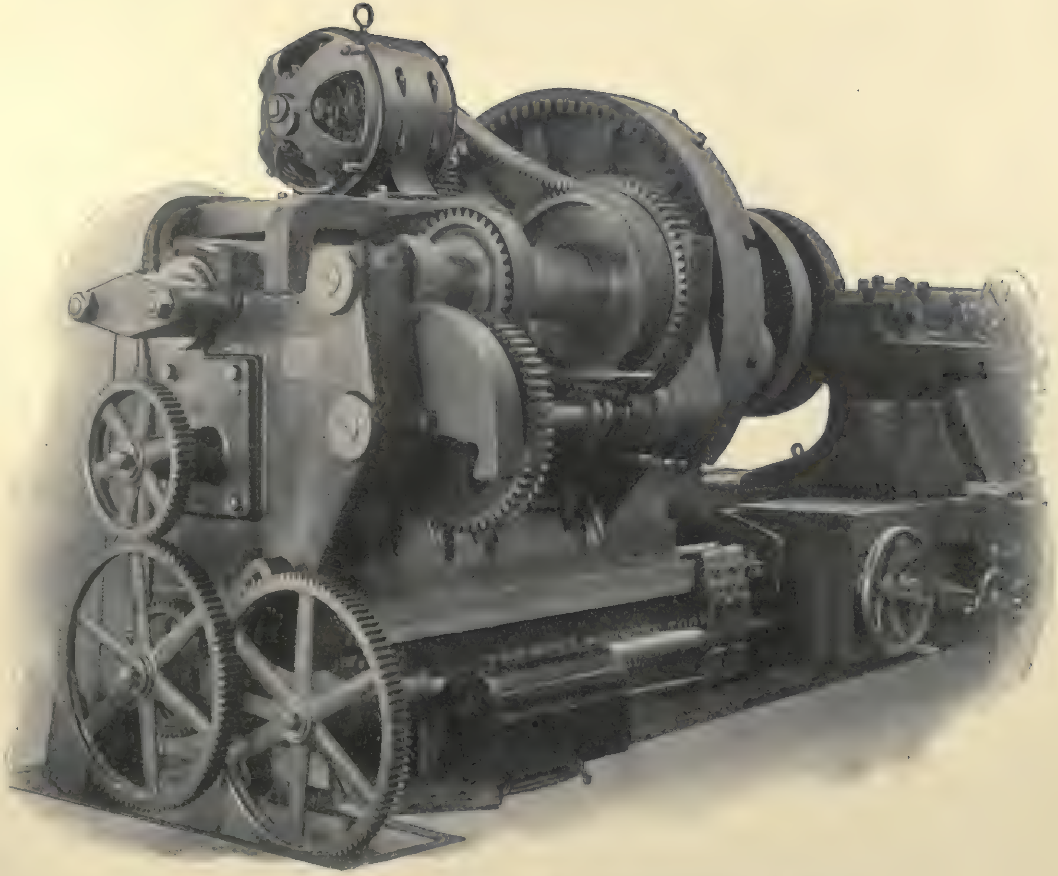
304 Longitudinal cross-section.
305 End elevation.
306 Plan.
307 Diagram of armature winding.
308 Details of important features.
309 Efficiency curve.
310 Curve of regulation.
311 Curves for losses from no load to rated load.
312 8 × 10½-in. paper required for description of method of calculation.

Drawings to be made with pencil on brown drawing paper, then traced and blue-printed.



LATHE EQUIPPED WITH CROCKER-WHEELER MULTIPLE-VOLTAGE APPARATUS.

Controller Arranged so that the Operator Can Start, Stop, and Obtain Any Spindle Speed Within Range of Motor, without Leaving His Work.



72-INCH LATHE DRIVEN BY 15 H.P. THOMPSON-RYAN MOTOR.

350–1750 Rev. per Minute.

Ridgway Dynamo and Engine Co.

DIRECT-CURRENT MOTORS

Comparison between Dynamos and Motors. The dynamo is a machine for the conversion of mechanical into electrical energy; conversely, the electric motor converts electrical energy into mechanical work. The electrical energy delivered by the dynamo must be obtained from a steam engine, water-wheel, or other power; and the mechanical power obtained from the electric motor comes from the energy of the current flowing through its armature. The two machines are exactly complementary; and, in the case of direct-current apparatus, we shall see that the same structure can be used for either service. The differences that are found in practice are largely mechanical, and arise chiefly from the conditions under which the motor must work.

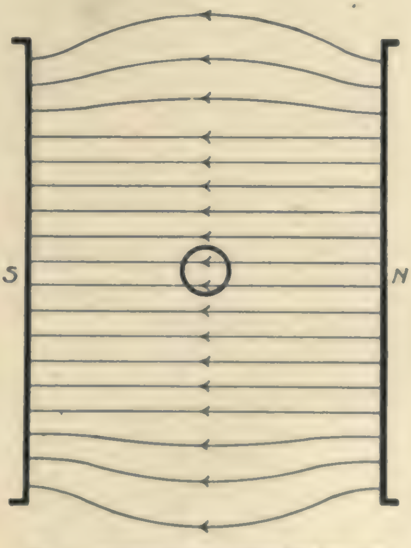


Fig. 1. Conductor Carrying No Current, in a Magnetic Field.

The study of the electric motor, therefore, begins with a knowledge of the dynamo; and before reading the following pages, the student should be sure that he understands fully the fundamental principles and mechanical details of Dynamo-Electric Machinery.

Force on a Conductor Carrying a Current. Fig. 1 represents a wire lying in a magnetic field, and carrying no current. If the polar surfaces of the field are large and close together, the magnetic lines pass straight from one to the other; they are not distorted, whether the wire is at rest or in motion. This is the condition in the air-gap of a dynamo or motor when no current is flowing in the armature conductors. The rotation of the armature in the magnetic field generates an electromotive force, but there is no mechanical force upon the conductors due to this action in itself. When, however, a current flows, it sets up a magnetic field of its own about the conductor, as shown in Fig. 2; and this field distorts the original field in which the conductor lies, making the magnetic lines denser on one side and less dense on the other. This is shown in Fig. 3.

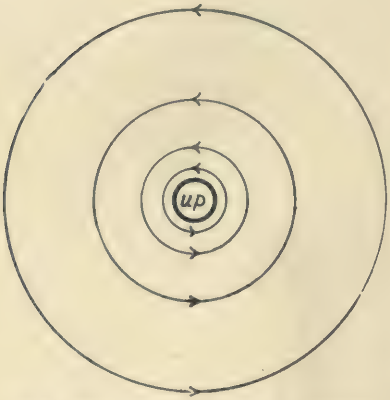


Fig. 2. Magnetic Field about a Conductor Carrying a Current.

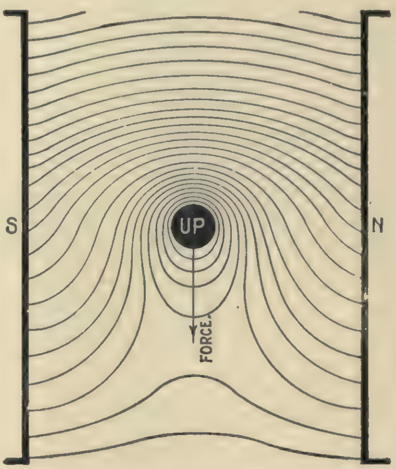


Fig. 3. Magnetic Field around Conductor in Dynamo or Motor Air-Gap.

Since the magnetic lines of a field endeavor to straighten and shorten themselves, the result of this distribution is a force upon the wire, pushing it in the direction of the arrow; and this is the principle of the electric motor. As in the dynamo, there are required: (1) a magnetic field; (2) a conductor lying perpendicular to it; and (3) provision for motion of the conductor across the field, in a direction perpendicular both to itself and to the field.

Fleming's Rule. The relation between the directions of the force, current, and magnetic lines can be most easily remembered by what is known as *Fleming's Rule.* Extend the forefinger, middle finger, and thumb, at right angles to one another; for example, the forefinger directly forward, the middle finger sideways, and the thumb upwards. Then if the forefinger represents the direction of the magnetic lines (that is, from the N pole through the air to the S pole), the middle finger will represent the direction of the current, and the thumb the direction of the motion. The right hand is to be used for the case of the dynamo, the left hand for the case of the motor.

Barlow's Wheel. An illustration of this principle is found in the simple electric motor invented by Peter Barlow in 1823, and illustrated in Fig. 4. A star-shaped metal wheel, usually of copper, rotates with its lowest points dipping into a little insulated pool of mercury. The wheel is connected through its bearings with one pole of a battery, the mercury to the other pole, the current flowing radially upward or downward through the wheel. When a horseshoe magnet is brought over the wheel, so that the portion carrying the current lies between the magnet-poles, the wheel revolves briskly, the direction of rotation changing whenever the direction of the current or the magnetic field is reversed.

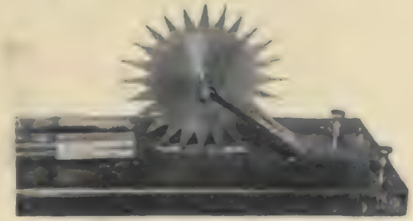


Fig. 4. Barlow's Wheel.

Magnitude of the Force on a Wire Carrying a Current. If the magnetic field has one line of force per square centimeter, and one absolute electromagnetic unit of current (10 amperes) is flowing in the conductor, the force upon each linear centimeter of the conductor will be one dyne. Hence, since the effects are directly proportional to the quantities involved, a wire L centimeters long, lying across a field of B lines per square centimeter, and carrying a current of I amperes, will be subjected to a force of:

$$L\ B\ \frac{I}{10}\ \text{dynes.}$$

This is practically a corollary of the definition of the ampere in electromagnetic measure.*

This expression may be reduced to the inch and pound units which are more common in American shop practice, by noting that one inch equals 2.54 centimeters; that one dyne is $\frac{1}{981}$ of the weight of a gram, nearly; and that 453.59 grams, or nearly 445,000 dynes, equal the weight of one pound. Hence the force F' upon

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*Consult S. P. Thompson's *Elementary Lessons in Electricity and Magnetism*, or any similar textbook on Electricity.

a wire L'' inches long, lying perpendicularly across a field of B'' lines per square inch, and carrying a current of I amperes, will be:

$$2.54\,L'' + \frac{B''}{(2.54)^2} \times \frac{I}{10}\text{ dynes;}$$

or,

$$F' = \frac{L''\,B''\,I}{2.54 \times 445{,}000 \times 10} = \frac{L''\,B''\,I}{11{,}303{,}000}\text{ pounds, approximately.}$$

Upon N similar wires, the force will be N times as great.

Example. Fourteen hundred conductors of a certain large armature, each 11 inches long, lie in magnetic fields of 42,000 lines per square inch. What is the total drag upon them when each carries a current of 60 amperes?

Solution. The force is:

$$\frac{1{,}400 \times 11 \times 42{,}000 \times 60}{11{,}303{,}000} = 4{,}318\text{ pounds, nearly.}$$

EXAMPLE FOR PRACTICE

Under the poles of a certain 25-kilowatt machine, there are 225 conductors, each $6\frac{1}{2}$ inches long, in magnetic fields of 40,000 lines per square inch. What current must flow in each conductor in order to give a total rotative force of 200 pounds?

ANS. 38.64 amperes, nearly.

In considering questions like the above, it is important to observe that only the conductors lying beneath the poles are subjected to these forces; and that the current in the individual conductors is not the full current of the machine, but only a fraction of it—one-half in the case of bipolar and wave-wound armatures; and one-fourth, one-sixth, or less, in the case of lap-wound armatures, according as the machine has four, six, or more poles.

It will now be clear that the driving force upon a dynamo armature must be increased in direct proportion to the load put upon the machine, and that the force causing a motor armature to rotate also depends on the current in it. The dynamo current is determined by Ohm's law, and the engine or water-wheel governor takes care of the power supply; but the way in which the electric motor adapts itself to the variations in its work, taking always just the necessary current for the work in hand, is not so clear at first sight. The explanation involves a most important property of the machine, known as the *counter-electromotive force.*

Counter-E.M.F. of a Motor. Since the armature wires rotate in magnetic fields, exactly as in the case of the dynamo, all the conditions for the generation of E.M.F. are fulfilled; and we should expect the motor armature to generate an E.M.F. accordingly, while in motion. The existence of such an E.M.F., and its direction, may be shown by the following experiment:

Take a small shunt-wound motor, and connect it as for ordinary running, but with the addition of a suitable incandescent lamp *L* and an ammeter *A* across the armature terminals, as shown in Fig. 5. When the motor is running, the lamp will glow, obviously supplied from the line; and the ammeter will show the direction of the current through it, as indicated by the arrow at *L*. The dotted arrows show the direction of the current in the other parts of the circuit. Now let the double-pole switch be opened; so far as the electrical conditions are concerned, the circuits may then be represented by Fig. 6; and the machine will run for a little while as a dynamo, driven by the energy stored in the rotating armature. The lamp still glows, and the ammeter shows that the current through it is in the original direction, dying out as the armature slows down to rest. Since the source of E.M.F. in the system is the revolving armature, and the direction of the current through the ammeter is known, it follows that in the other parts of the circuit the current must flow as indicated by the dotted arrows in Fig. 6. The reversal of the current in the armature can be shown directly by putting a second ammeter into the armature circuit, as indicated at *B*, Fig. 6, but the experiment can be performed equally well without it.

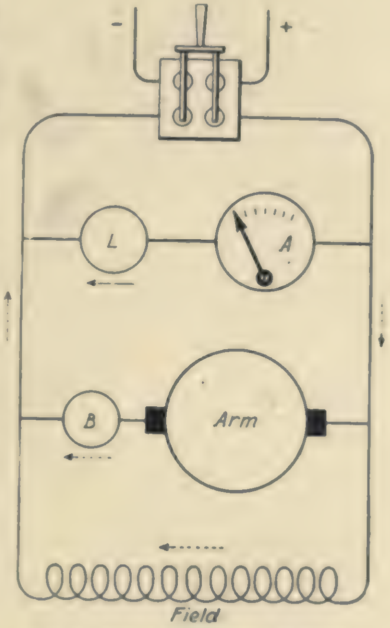


Fig. 5. Motor Connections to Show Counter-E.M.F.

This experiment is very instructive if performed with a motor of several horse-power. The experimenter should prevent the arm of the starting rheostat from flying back until the armature has entirely ceased to revolve.

A comparison of Figs. 5 and 6 now brings the conclusion that the direction of the current in the various parts of the circuit must be due to the existence of an E.M.F. in the revolving motor armature which is opposite in direction to the line E.M.F., and hence opposes the flow of current through the armature. For this reason it is called the *counter-E.M.F.* The electrical difference, therefore, between a dynamo and a motor is that in the dynamo the current flows *with* the E.M.F. of the armature, while in the motor it flows *against* it.

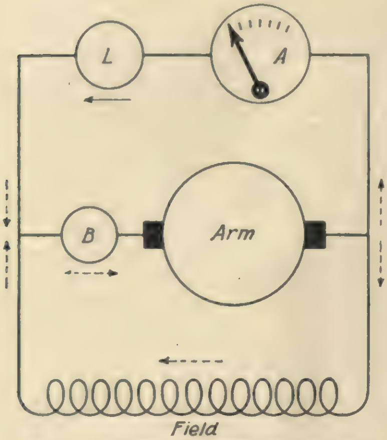


Fig. 6. Currents in Motor Circuits after Opening Main Switch.

Fundamental Motor Equation. From the above it follows that the current through the revolving motor armature is always less than the value obtained by simple calculation from Ohm's law, because E, the line E.M.F., is partially neutralized by e, the opposing counter-E.M.F. Hence the fundamental motor equation may be written:

$$I = \frac{E-e}{R}, \quad \ldots\ldots\ldots\ldots\ldots \quad (1)$$

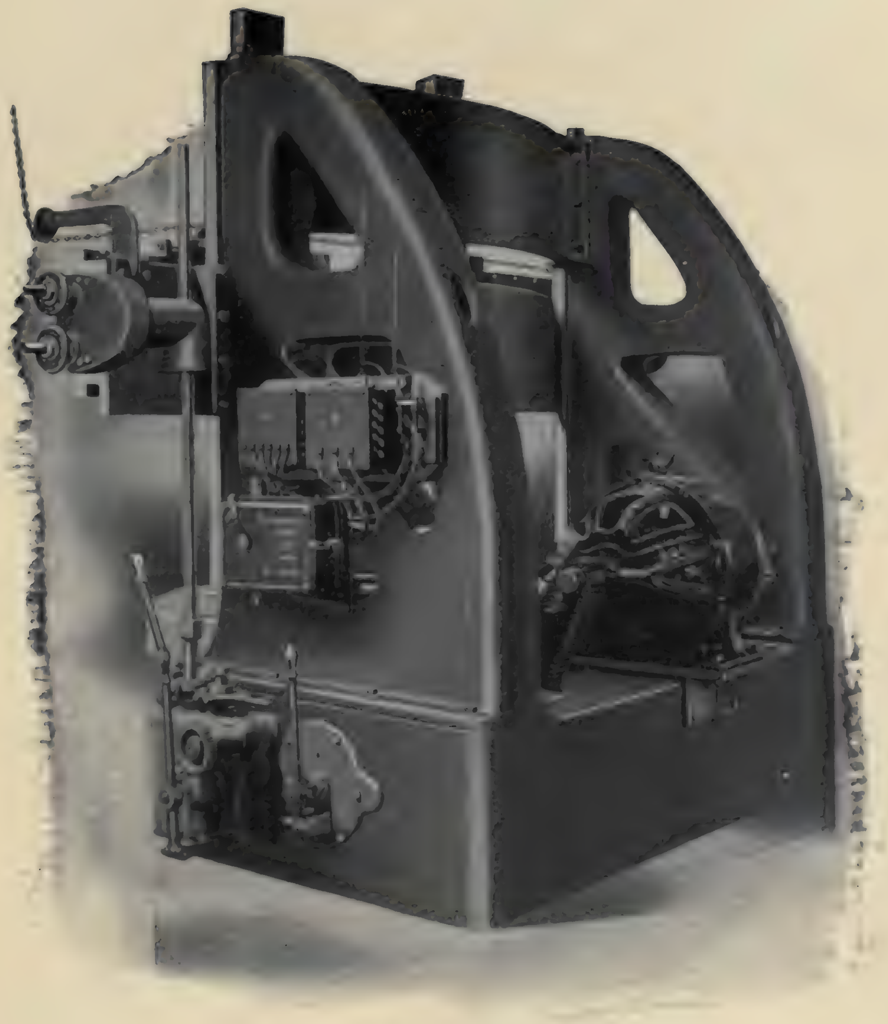
in which I represents the current through the armature, and R the resistance of the armature circuit—armature, brush gear, and any other resistance that may be present.

The counter-E.M.F. is not readily measured; it is best calculated from Equation 1 with a knowledge of the other three quantities, which are easily measurable.

Example. A certain motor armature with its brush gear has a resistance of 0.188 ohm; and when running at a certain speed, takes a current of 55 amperes from a 220-volt line. What counter-E. M. F. is developed under these conditions?

Solution. Substituting the given values in Equation 1, we have:

$$55 = \frac{220 - e}{0.188};$$



7-FOOT VERTICAL BORING AND TURNING MILL.
Motor Driven.
The J. Morton Poole Company.

whence,

$$e = 209.66 \text{ volts.}$$

EXAMPLE FOR PRACTICE

What current will flow through the above armature when its counter-E.M.F. is nine-tenths of the line voltage?

ANS. 117 amperes, nearly.

From these considerations it is plain that in the absence of other resistance in the armature circuit than that of the armature itself, a slight change in the counter-E.M.F. may make a great difference in the strength of the current flowing. Further, since the figures are taken from actual machines, it is to be noted that under ordinary running conditions the counter-E.M.F. rises well up toward the value of the line E.M.F. It can of course never quite equal the line E.M.F., for in that case no current would flow; and even when running without load, the friction and electrical losses of the motor absorb some power, so that a small fraction of the full-load current will flow, though the armature delivers no power at the pulley.

Efficiency and Losses. The energy-losses of the motor are the same as those of the dynamo, and may be classified under two heads:

Electrical Losses:

(*a*) I^2R losses in armature conductors and brush gear.
(*b*) I^2R losses in field windings.

Stray-Power Losses:

(*c*) Friction: of bearings, brushes, and air-currents.
(*d*) Iron losses: eddy currents in armature core, teeth, and magnet-poles; hysteresis in armature core and teeth.
(*e*) Commutator losses: wasteful currents in coils during commutation.
(*f*) Eddy currents in armature conductors.

The electrical losses (*a*) and (*b*) are measurable without much trouble; the others are very difficult to obtain separately, and are usually taken together under the general name *stray power*. For shunt motors, the field I^2R loss is independent of the load; the armature I^2R, of course, varies with the load. In the series motor, both field and armature I^2R vary with the load, since the same current passes through both. The stray-power loss is nearly constant for ordinary operating conditions, though it increases slightly with the speed of the armature.

The commercial efficiency η of a motor is simply the fraction of the power supplied that is available at the shaft; that is, it is the ratio of the power delivered to the power supplied; or, in the form of an equation:

$$\eta = \text{Efficiency} = \frac{\text{Output}}{\text{Input}} = \frac{\text{Input} - \text{Losses}}{\text{Input}} \quad . . . (2)$$

The following table shows average values for the commercial efficiency of ordinary motors of various sizes, at full load:

TABLE I

Commercial Efficiency of Ordinary Motors

FULL LOAD H.P.	EFFICIENCY (Per Cent)
0.02 (Fans)	30
0.05 "	42
0.1	50
0.5	63
1.	70
5.	82
10.	85
25.	88
50.	89.5
100.	91
200.	92.5

The low figures for small motors are caused by disproportionately large field I^2R and friction losses.

Variation of Efficiency with Load. The efficiency varies with the load, because some of the losses are constant and some variable, the chief variable being the armature I^2R. When the motor is running idle, the current is small, and all its energy goes to supply the losses, the commercial efficiency being therefore zero. As the motor is loaded, the output at first increases faster than the losses, and the efficiency rises rapidly, reaching a maximum at a certain load which depends on the design of the machine. When the load is very heavy, the great increase in the armature I^2R causes the efficiency to fall again.

The efficiency is a maximum when the constant and variable losses are equal—for example, in the case of a shunt motor, when the armature I^2R loss equals the sum of the stray-power and field I^2R losses.* Since the distribution of the losses may be controlled by

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* This proposition may be proved by algebraic methods, as follows:

Denoting by S the sum of the field I^2R loss and the stray power, the efficiency may be written:

$$\eta = \text{Efficiency} = \frac{EI - I^2R - S}{EI} = 1 - \left(\frac{IR}{E} + \frac{S}{EI}\right).$$

the designer within fairly wide limits, it follows that a motor (or a dynamo) may be designed to show its maximum efficiency at any specified fraction of its full load, or even at overload, though the latter is unusual. Motors should be designed to have their maximum efficiency with the load at which they are most used. An ordinary shop motor should show a maximum at about 75 per cent of its full rated load; a street-railway motor, at about two-thirds of the maximum power it is expected to develop (see Fig. 33); a fan motor, at its full load; and so on. A motor with large constant losses and small variable losses will have a low efficiency at light loads, and a high one at full load; while a machine with small constant and large variable losses will have a much higher efficiency at light loads than at full load. The most important point is not the full-load efficiency, but rather the maximum efficiency, coupled with another figure which we may call the *all-day efficiency.*

All-Day Efficiency. This is a matter of some importance in practice. It is simply the ratio between the work obtained from the motor during the day, and the energy taken from the line in the same time.

The difference between the performances of different machines in this respect, is best shown by an example. Suppose we have two 100-horse-power motors, motor A having constant losses of 2,700 watts, and armature I^2R losses of 6,400 watts; and motor B having constant losses of 4,800 watts, and armature I^2R losses of 3,200 watts. Suppose them to run through a 9-hour day, and that

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For maximum efficiency, it is plain that $\frac{IR}{E} + \frac{S}{EI}$ must be a minimum; or, since E is a constant, that $IR + \frac{S}{I}$ must be a minimum. The sum of these two terms will be large when I is either very large or very small, and the problem is to determine the particular value of I for which it will be smallest. Denoting the sum by k, we may write:

$$IR + \frac{S}{I} = k, \quad \ldots\ldots\ldots\ldots \quad \textbf{(a)}$$

which is a quadratic equation in I. Solving this by ordinary algebra gives:

$$I = \frac{k}{2R} \pm \frac{1}{2R}\sqrt{k^2 - 4\,RS} \quad \ldots\ldots \quad \textbf{(b)}$$

Now, since a negative quantity cannot have a square root, the quantity under the radical sign cannot be less than zero, and therefore the smallest value k can have will be determined from the equation:

$$k^2 - 4\,RS = 0. \quad \ldots\ldots\ldots\ldots \quad \textbf{(c)}$$

Inserting in (a) the value of k obtained from (c), and reducing gives as the final result $I^2R = S$; or, in other words, when a motor is working at its highest efficiency, the armature current is such as to make the variable losses just equal to the constant losses.

they run for 2 hours at quarter-load, 4 hours at half-load, and 3 hours fully loaded; let us calculate the energy actually delivered, and the energy taken from the line. Remembering that 1 H.P. = 746 watts, and that the I^2R loss varies as the square of the current, we have, for motor A, the following:

Constant Losses:	2,700 watts for 9 hours,	24,300 watt-hours.
I R Losses:	$\frac{1}{16}$ of 6,400 watts for 2 hours,	800 "
	$\frac{1}{4}$ of 6,400 watts for 4 hours,	6,400 "
	6,400 watts for 3 hours,	19,200 "
Output:	$\frac{1}{4}$ of 74,600 watts for 2 hours,	37,300 "
	$\frac{1}{2}$ of 74,600 watts for 4 hours,	149,200 "
	74,600 watts for 3 hours	223,800 "
	Input for the day:	461,000 watt-hours.

The all-day efficiency is therefore:

$$\frac{\text{Output}}{\text{Input}} = \frac{410,300}{461,000} = 89 \text{ per cent}$$

For motor B, we have:

Constant Losses:	4,800 watts for 9 hours,	43,200 watt-hours.
I^2R Losses:	$\frac{1}{16}$ of 3,200 watts for 2 hours,	400 "
	$\frac{1}{4}$ of 3,200 watts for 4 hours,	3,200 "
	3,200 watts for 3 hours,	9,600 "
Output:	as for motor A,	410,300 "
	Input for the day:	466,700 watt-hours.

Hence the all-day efficiency is:

$$\frac{410,300}{466,700} = 87.9 \text{ per cent.}$$

Thus, although motor B has a higher full-load efficiency than motor A (90.3 per cent as compared with 89.1 per cent), the latter returns the larger percentage of the energy put into it during the day, the difference being 5,700 watt-hours, or 5.7 kilowatt-hours in favor of A. It is thus seen to be a matter of some importance to keep the constant losses down to the lowest point consistent with satisfactory operation in other respects; and machines should be selected by the purchaser with reference to this point, as well as for full-load efficiency. For this reason the efficiency values at different loads may vary several per cent in motors of different but equally good design; and the figures in the preceding efficiency table must be regarded as only approximate. Most shop and factory motors are subjected to very variable loads; and the average load of a large number of motors in a given plant will often be found to be considerably less than 25 per cent of the total rated capacity of the motors in circuit. With motors designed upon the lines mentioned above, it may be said that the saving at average day loads would range from 4 per cent to 10 per cent in the larger motors (from 60 to 120 horse-power), up to a saving of 8 per cent to 15 per cent in the smaller motors.*

EXAMPLE FOR PRACTICE

Suppose a 100-horse-power motor were designed so as to have constant losses of 6,400 watts and armature I^2R losses of 2,700 watts, and that it works under the same conditions as those given for motor A in the preceding example. What would its all-day efficiency be, and how much more energy would it take from the lines in one day than motor A? Ans. 85.7 per cent; 18 + kilowatt-hours.

Current Required by Motors. The value of the full-load current is usually stamped upon the name-plate of the machine. If not, it can be approximately found from the rated output by assuming a value for the efficiency.

Example. What current will be required by a 220-volt, 15-horse-power motor?

Solution. From Table I (p. 8), the efficiency may be taken as 86 per cent. The output is:

$$15 \times 746 = 11,190 \text{ watts.}$$

The input is:

$$\frac{11,190}{0.86} = 13,012 \text{ watts.}$$

The current is therefore:

$$\frac{13,012 \text{ watts}}{220 \text{ volts}} = 59.1 \text{ amperes.}$$

EXAMPLES FOR PRACTICE

1. A 50-horse-power motor is connected to a 500-volt line which will carry 60 amperes. Can the motor be operated at full load? Ans. No.

2. Assuming an efficiency of 88 per cent, what is the maximum power that can be obtained from the above motor without overloading the line? Ans. 35.4 horse-power, nearly.

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*Hobart. *Electric Motors*, 1904.

Effect of Counter-E.M.F. on Efficiency. At first sight it might appear that the counter-E.M.F. is merely an incident of operation, or at least a hindrance to the best performance of the machine; but a more careful study of the question shows that it is an essential factor in the economy of the motor. This can be most clearly shown by taking the artificially simple case of a motor whose only losses are the armature I^2R. This would be very nearly realized by a frictionless magneto-motor. Its efficiency η would be:

$$\eta = \frac{\text{Input} - \text{Losses}}{\text{Input}} = \frac{EI - I^2R}{EI} = \frac{E - IR}{E}. \quad \ldots (3)$$

But,

$$I = \frac{E - e}{R};$$

whence,

$$IR = E - e.$$

Substituting this value of IR in Equation 3, we have:

$$\eta = \frac{E - (E - e)}{E} = \frac{e}{E}. \quad \ldots\ldots\ldots (4)$$

That is, the efficiency is directly proportional to the counter-E.M.F.

This proposition is known as *Siemens' Law of Efficiency.* It should not be understood as implying anything concerning the output. The current taken by the motor diminishes as the counter-E.M.F. rises; and the power delivered also diminishes as the armature approaches full speed. But the equation does mean that the power delivered per ampere taken from the line is greater as the value of e approaches E; and therefore, though the actual power delivered is less, the available *percentage* of the line energy is greater than if the actual output were larger. For this reason it is entirely possible to operate a motor beyond its rated capacity, though at a reduced efficiency, the permissible amount and duration of the overload depending chiefly on the time required for the increased losses to heat up the machine dangerously.

In the actual motor, where other losses enter, the case is not quite so simple and direct as the above; but the difference is small, the complete equation being:

$$\eta = \frac{e - \frac{S}{I}}{E},$$

in which S is the sum of the field I^2R and the stray power, as on page 8. The fraction $\frac{S}{I}$ is only a few per cent of E, in ordinary running under load, so that the Siemens law holds, except for small values of I—that is, for light loads.

So it follows that the counter-E.M.F. is a valuable property of the motor, to be cultivated rather than ignored or eliminated; and the lack of success of early types of motors was in part due to a failure to realize this. In other words, the motor should be designed and operated to generate an E.M.F. exactly like a dynamo; and the formula for efficiency shows that the electrical and mechanical losses should be kept as small as practicable. The requirements for dynamos and motors are therefore the same, and it should now be clear that they must be designed along the same electrical lines. Consequently they are interchangeable.

The fact that a dynamo will transmit power to a similar machine as a motor is said to have been brought to light by a Paris workman in 1873, who accidentally connected the wires of an idle dynamo to the terminals of one in operation, whereupon the motionless armature immediately started up at full speed. The discovery of the general principle of interchangeability, however, dates back to 1852, and perhaps earlier.*

Torque. The torque of a motor is the turning moment or twist exerted upon the shaft. Grasp the pulley of a small motor firmly in the hand, and close the switch; a strong twisting action will be felt, which will set the armature in rapid rotation when freed. With the armature stationary, the torque is sometimes called *static torque*, to distinguish it from the *running torque* of the rotating armature, available at the pulley; the latter is less than the former by the amount necessary to overcome armature friction and core losses.

Since torque is caused by a force acting at the end of a lever arm, it is measured by the product of the force and the length of the arm—for example, by the product of the working pull of the belt and the radius of the pulley; or by the force upon the armature wires, multiplied by their average distance from the axis of the shaft. This product is generally expressed in *pound-feet*, which term denotes the

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*S. P. Thompson. *Dynamo-Electric Machinery*. Edition of 1888, p. 18.

pull in pounds multiplied by the length of the lever arm in feet.* Thus a torque of 60 pound-feet may represent a working belt-pull of 60 pounds on a pulley 1 foot in radius, or a pull of 72 pounds on a pulley whose diameter is 20 inches, or any other combination of force and arm whose product is 60 pound-feet. For simplicity, torque is sometimes expressed in pounds only, a radius of one foot being understood or implied; but this is liable to cause confusion, because torque is not a force, but the moment of a force, and the radius of its action should always be given.

EXAMPLE FOR PRACTICE

If a motor has a torque of 40 pound-feet, what pull will be exerted at the rim of a pulley 16 inches in diameter?

Ans. 60 pounds.

The torque of a motor may be measured by means of a Prony or friction brake. The arrangement of the apparatus is shown in Fig. 7. *P* is the motor pulley, *A* and *C* blocks of hardwood clamped against it, the pressure being regulated by the wing-nuts *e e*. The lever *L*, which may be of any convenient length, is counterbalanced by the weight *w*. When the pulley rotates in the direction of the arrow, the friction on the blocks tends to raise the weight *W*; and by adjusting the pressure on the blocks and varying *W*, a balance may be obtained, so that *W* when hanging free just neutralizes the tendency of the lever *L* to revolve. The torque of the motor is then $W \times R$, where R is the perpendicular distance from the axis of the shaft to the line of support of *W*.

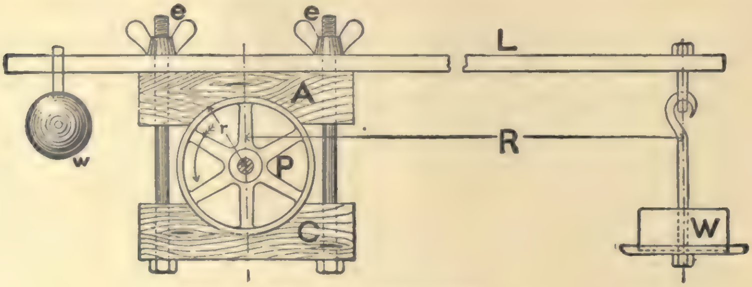

Fig. 7. Friction Brake.

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* The term *foot-pounds* should not be used in this connection, for the foot-pound is a commonly used unit of work, and torque by itself is not work.

To find the torque when the motor is running at a certain speed or is taking a certain current, the nuts *e e*, must be adjusted until the speed or current is as desired, preventing the lever *L* from revolving by stops, and then varying *W* until a balance is obtained, when the stops are taken away. In making the measurement, it may be necessary to allow a little water to run upon the inside of the pulley, to absorb the heat generated by the friction. The wood blocks run best when dry, and a little smoke does no harm to the measurement. Instead of an adjustable weight *W*, a spring balance is more convenient. This is a very satisfactory method of testing small motors; for large ones, the heat is too great to be readily dissipated unless a special pulley is used which will hold water inside the rim.

The *power* of a motor is the product of the torque and the speed. For, if a force *W* acts at the end of an arm *R* fastened to a shaft, in one revolution the distance traversed by the point of application of the force is $2 \pi R$, and the work done $2 \pi R \times W$. In the case represented by Fig. 7, the work done by the revolving shaft is the same as if a weight *W* were being continually wound up on a pulley of radius *R*. If the shaft revolves *N* times per minute, the work done per minute is $2 \pi R W \times N$; or, since RW is the torque, we may write:

$$\text{Power} = 2 \pi \times \text{Torque} \times \text{Speed} \quad \ldots\ldots\ldots (5)$$

Denoting the torque by T, we have the further result:

$$\text{Horse-Power} = \frac{2 \pi T N}{33{,}000} \quad \ldots\ldots\ldots (6)$$

From Equations 5 and 6, it follows that different motors of the same power may have very different properties. They may give a strong torque at low speed, or a light torque at high speed, or may have intermediate values of both, different kinds of work requiring one property or the other. From the discussion on page 3, it follows that the actual force upon the armature wires depends upon their number and on the strength of the field, and the torque will also vary with the diameter of the armature. A strong torque will therefore be obtained by using an armature of large diameter, with many wires revolving in a strong field; but since these are just the conditions for a high E.M.F., such an armature will generate its full counter-E.M.F. at a lower speed than a smaller armature with fewer wires; that is, for a given voltage, the high-torque armature will run at relatively slow speed.

With the aid of Equation 6, it is a simple matter to measure the output of a motor by the brake.

Example. For a certain motor the distance R was 30 inches, the weight W 12.4 pounds, and the speed 1,400 revolutions per minute. What horse-power was developed?

Solution. Since R must be expressed in feet,

$$T = 2.5 \times 12.4 = 31 \text{ pound-feet.}$$

Substituting this value of T in Equation 6, gives:

$$\text{Horse-Power} = \frac{2 \times 3.1416 \times 31 \times 1{,}400}{33{,}000} = 8.25. \qquad \text{Ans.}$$

EXAMPLE FOR PRACTICE

A 500-volt motor rated at 15 horse-power takes a current of 25 amperes when driving a certain machine. It is then disconnected and fitted with a brake; and a test shows that with $R = 32$ inches, and the wing-nuts adjusted until the current is 25 amperes, the speed is 755 revolutions per minute; and $W = 36$ pounds. What is (*a*) the actual horse-power needed to drive the machine; and (*b*) the efficiency of the motor?

Ans. 13.8 horse-power, nearly.
82.3 per cent.

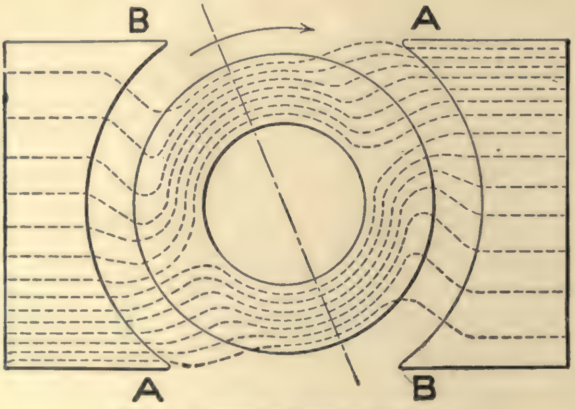


Fig. 8. Armature Reaction in Motor.

Armature Reaction in Motors. In a motor the direction of the armature current, and hence the direction of its magnetic field, are opposite to those in a generator. The resultant field in the motor armature and air-gap will therefore be as shown in Fig. 8. It is evident that the neutral points are shifted backwards, while in a generator they are shifted forwards; hence for good commutation the brushes must be shifted *against* the rotation, while in the dynamo they are shifted *with* it. Most motors are required to operate without change of brush lead throughout the entire range of load; and this necessitates careful design, to the end that the field-magnets shall entirely overpower the armature reaction and keep the distortion of the field small, so that commutation may be good with the brushes fixed in position, no matter what the load may be. Many motors, particularly railway motors, must in addition run in either direction; and this requires fixing the brushes at the no-load neutral point. Such motors, however, cannot give as good commutation as those in which the brushes may be set backwards—a fact which is shown by the more rapid roughening and wear of the commutator and brushes. Nearly all motors are operated on constant-potential circuits, and carbon brushes are used almost without exception.

General Speed Formula. The factors upon which the speed of a motor depends can be obtained as follows:

The counter-E.M.F. depends upon the strength of the field f, the number of armature conductors z, and the speed of rotation s. Hence we may write $e \propto s f z$, or, in the form of an equation,

$$e = k s f z,$$

in which k is a constant depending on the design of the motor. Substituting this value of e in Equation 1, we have:

$$I = \frac{E - e}{R} = \frac{E - k s f z}{R};$$

and, solving for s,

$$s = \frac{E - IR}{k f z} \quad \ldots\ldots\ldots\ldots \quad (7)$$

As already stated, IR is only from 3 per cent to 5 per cent of E in motors of ordinary size; and if we disregard it, we may write the simple relation:

$$s = \frac{E}{k f z} \quad \ldots\ldots\ldots\ldots \quad (8)$$

That is, the speed of a motor is directly proportional to the E.M.F. at the brushes, and inversely proportional to the number of conductors on the armature and the strength of the field.

Other conditions remaining the same, it is plain that an increase in E will increase the speed, for increased E increases the current and therefore the torque, and the speed must evidently rise as an immediate consequence. But at first sight it is not so clear that the same result will be produced by weakening the field. The reason may be seen, however, by anticipating the result of the calculation on page 20, where it is shown that any reduction of the counter-*E.M.F.* increases the current in a much greater ratio. In the example there given, reducing the field strength 1 per cent increases the armature current 24 per cent, so that the actual increase in the torque is $\frac{99}{100}$ of 24 per cent (or 23.76 per cent), or practically in proportion to the current. Hence the speed increases, the increased current much more than compensating for the slight diminution in the field strength.

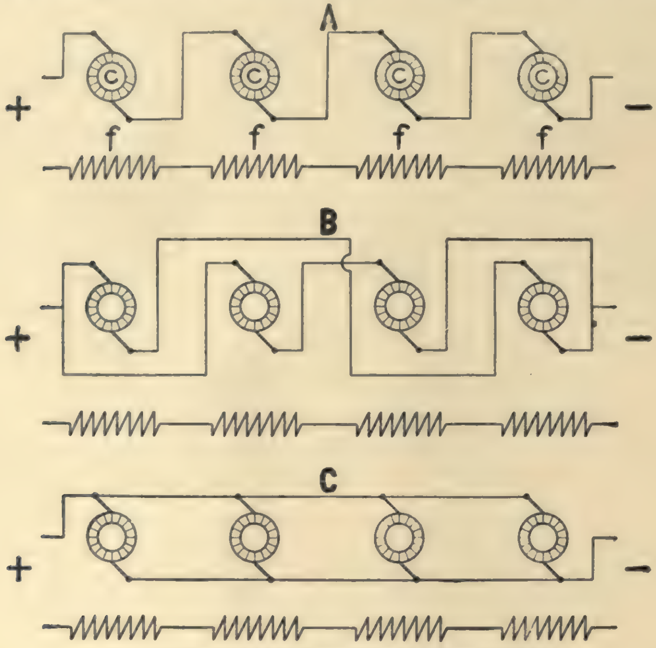


Fig. 9. Series-Parallel Connections of Four Motors.

It is often desirable to vary the speed of a motor, and Equation 8 thus gives the three general methods for accomplishing the desired result—namely:

(1) By varying the E.M.F. at the brushes.
(2) By varying the strength of the field.
(3) By changing the number of wires on the armature.

Of these, methods 1 and 2 differ in details with different types of motor, and are discussed under each type. Method 3 is not practicable, since for satisfactory operation it would involve several independent windings, each with its own commutator. But where several motors drive one machine, the same result can be obtained by connecting the motor armatures in series or parallel combinations. Thus two motors may have their armatures connected in series or parallel by a suitable switch or controller; in the first case, half the line E is supplied to each armature; in the second case, the full E. With four motors the connections might be made as shown in Fig. 9, giving speeds in the ratio 1 : 2 : 4 with the arrangements A, B, and C, respectively, the motor fields f being kept constant. In the actual case, however, two-motor or four-motor combinations are used only in railway work; and four-motor sets are operated with the motors connected in pairs, like a two-motor equipment; in the latter case the additional flexibility of operation does not justify the extra complication introduced by taking the four as separate units. In general, this method of speed regulation is favorable to economical working, for the use of wasteful resistances is much reduced; but it does not warrant the installation of two motors when one will do the work.

CLASSES OF MOTORS

The preceding propositions are true for all classes of direct-current motors; but there are also many special properties depending on the relations that exist between the armature and field, so that it is next necessary to classify motors, like dynamos, with respect to the different methods of exciting the field. We have, accordingly:

1. Magneto motors.
2. Shunt motors.
3. Series motors.
4. Compound motors.

Magneto Motors. Because of the difficulty of making them self-exciting, very small dynamos are built with permanently magnetized fields. With motors, however, there is no such difficulty in obtaining the field, so that the magneto motor is not used, except where rotation in one direction or the other is desired by simply reversing the current without further complication. This is sometimes required in light mechanisms or controlling apparatus.

SHUNT MOTORS

To this class belong most of the motors used for all direct-current power service except railway work. The construction and electrical connections are exactly the same as for shunt dynamos, and any good shunt dynamo will make a correspondingly good motor. Shunt motors are practically always operated on constant-potential circuits, and, except at starting, the electrical connections are as shown in Fig. 10, both armature and field being connected across the line. Hence the field current and the field strength will be constant, and the torque will vary directly as the current through the armature, the current itself being determined by Equation 1.

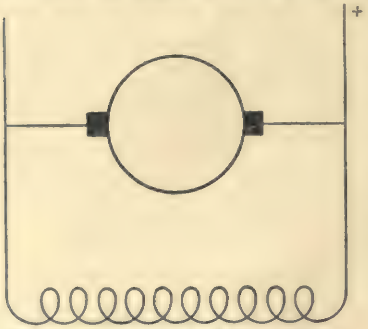


Fig. 10. Connections of Shunt Motor when Running.

The action of the shunt motor may be explained as follows:

Since the counter-E.M.F. varies as the product of the speed, strength of field, and number of armature wires, and the two latter factors are constant in this case, it follows that any change in the speed will cause a proportionate change in the counter-E.M.F. e; but, since e is nearly equal to E (the line E.M.F.), the current through the armature will change in a much greater ratio, a small decrease in the counter-E.M.F. causing a much greater increase in the current, and hence in the power delivered by the motor. For example, if the counter-E.M.F. of a 125-volt motor is 120 volts at a speed of 1,000 revolutions per minute, and the armature resistance is 0.2 ohm, the current at this speed is:

$$\frac{E - e}{R} = \frac{125 - 120}{0.2} = 25 \text{ amperes.}$$

If an additional load is put upon the armature, it naturally slows down. Suppose it to slow down to 990 revolutions per minute. The counter-E.M.F. will then decrease to $\frac{990}{1,000}$ of 120, or 118.8 volts; and the current will rise to:

$$\frac{125 - 118.8}{0.2} = 31 \text{ amperes.}$$

That is, a decrease of 1 per cent in the speed causes an increase of 24 per cent in the current; and the speed will continue to diminish until the current increases enough to supply sufficient power to prevent further speed reduction—that is, until the increased input equals the increased demand. Similarly, a diminished load which will allow the armature to speed up to 1,100 revolutions per minute will be accompanied by a decrease of 24 per cent in the current. Small variations of speed like this are not readily noticed; and to the casual observer the motor seems to adapt itself with uncanny knowledge to its work, in taking without apparent effort the precise current for every demand. The explanation lies, as we see, in the fact that only a slight change is needed in the delicate balance between E and e to accomplish the observed result, by speed variations which are usually too small to notice, unless very sudden. If the load should be removed entirely, there is no tendency for the motor armature to race, for every slight increase in the speed increases e and diminishes the flow of current from the line, thus cutting off the power supply when it is not wanted.

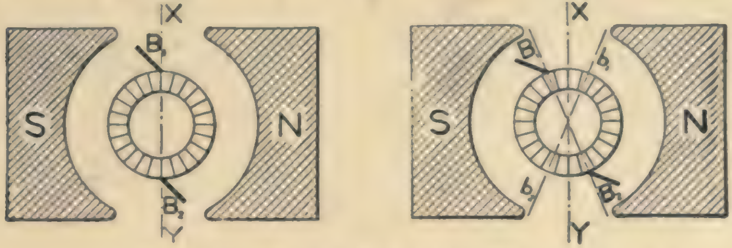


Fig. 11. Demagnetizing Effect of Motor Armature.

The smaller the value of R, the greater will be the change in I for a given change in e; in other words, the smaller will be the variations in speed with changes of load. Since e differs from E by IR, the E.M.F. required to send the current through the ohmic resistance of the armature, and in well-designed machines IR is only from 3 per cent to 5 per cent of E, the speed falls off from no load to full load only by this small percentage; and we have in consequence the very valuable ability of the shunt motor to run at practically constant speed, irrespective of the load upon it. The small variations that actually do occur are not, as a rule, of sufficient importance to warrant special devices for their correction.

EXAMPLE FOR PRACTICE

Calculate the current through the above-mentioned motor when the speed is 1,100 revolutions per minute.

ANS. 18.95 amperes.

Effect of Armature Reaction on Speed. To eliminate sparking, we have seen that it is necessary to shift the brushes of a motor backward, and those of a generator forward. In both cases, there is introduced a demagnetizing belt of conductors, which weakens the field. This is illustrated in Fig. 11, which shows the motor brushes drawn backward from the no-load position. This action creates a demagnetizing belt of conductors lying between B_1 and b_1, and between B_2 and b_2. As the motor is loaded, the field is therefore progressively weakened by the increased current through this belt of conductors, and the counter-E.M.F. reduced correspondingly, which tends to increase the speed. Thus, by giving considerable backward lead to the brushes, it is possible to obtain nearly constant speed at all loads. Not all motors are designed to operate with so great a lead as this would often require; but the effect is always present in some degree, to the further advantage of the constant-speed tendency of the shunt motor.

Speed of Shunt Dynamo Used as Motor. If a shunt dynamo is used as a motor on a line of the same voltage, its speed as a motor will be less than when generating the line voltage as a dynamo. To find what the motor speed will be, we may proceed as follows:

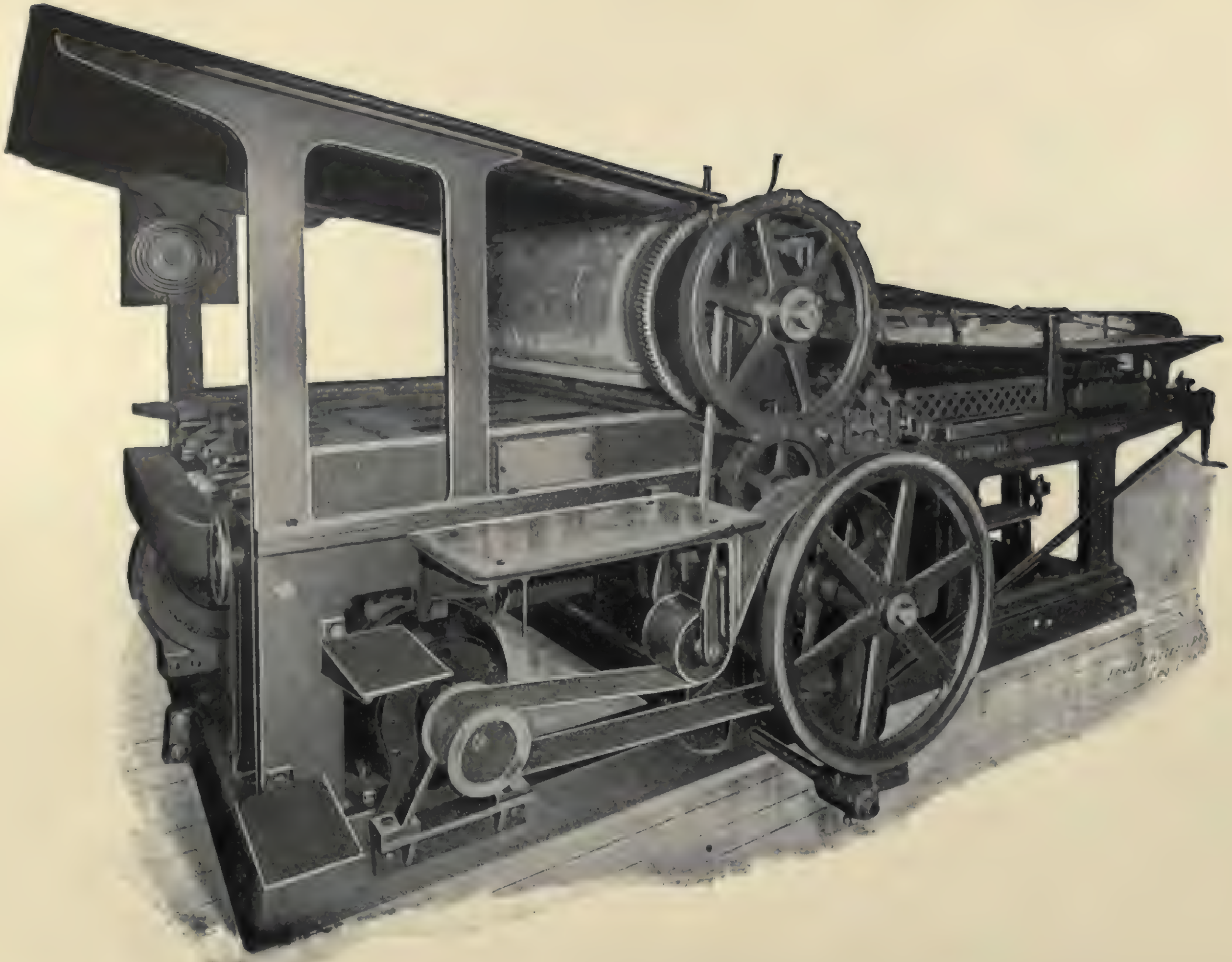
To supply I amperes to the line at E volts, E_d, the E.M.F. generated in the armature, must be $E_d = E + IR$, where R is the armature resistance, because some of the E.M.F. generated is expended in sending the current through the armature itself. The E.M.F. generated in the armature of the same machine used as a motor is, from Equation 1:

$$e = E - IR.$$

Since the field strength is the same in the two cases, both being supplied at E volts, the armature E.M.F.'s will be directly proportional to the speed; or,

$$\frac{\text{Motor Speed}}{\text{Dynamo Speed}} = \frac{e}{E_d} = \frac{E - IR}{E + IR} = 1 - \frac{2\,IR}{E}, \text{ approximately. . } \quad (9)$$

Since $\frac{IR}{E}$ lies ordinarily between 0.03 and 0.05, as we have seen,



ROUND TYPE MOTOR BELTED TO CENTURY PRINTING PRESS.

Sprague Electric Company.

it follows that the speed of a given machine as a motor will be generally from 6 per cent to 10 per cent less than its speed as a dynamo. If, however, the field strength is not constant, either because of armature reaction or changes in the field current, the relation, of course, ceases to hold.

EXAMPLE FOR PRACTICE

A certain dynamo is rated at 25 kilowatts at 220 volts and 600 revolutions per minute. Its armature resistance is 0.08 ohm. What is its full-load speed as a motor? Ans. 550 r.p.m.

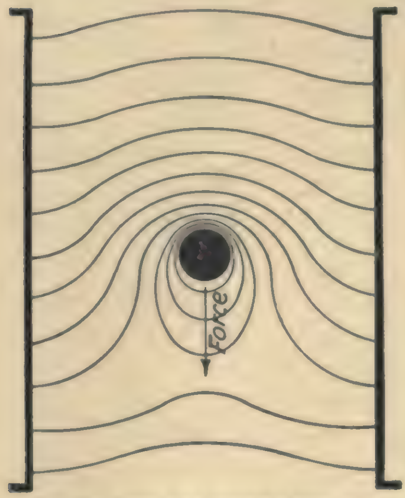


Fig. 12. Force on Dynamo Armature Conductor Moving Upward.

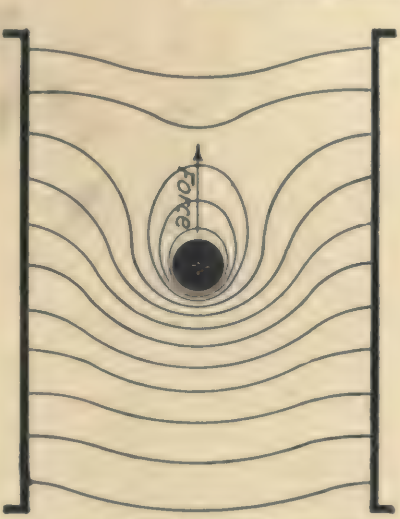


Fig. 13. Force on Motor Armature Conductor Moving Upward.

Direction of Rotation of Shunt Motor. To examine the behavior of a shunt dynamo used as a motor, a modification of Fig. 3 may be used. Fig. 3 gives the general directional relations between the field, current, and force upon an armature conductor; and Fig. 12 represents the case of a wire on a dynamo armature, moving toward the top of the page, the current creating a force on the wire which is against the direction of the motion, so that power is required to keep up the rotation. Now, if the machine is used as a motor driven by current from the same line, the direction of the field remains the same; but the current through the armature is reversed, and the field of Fig. 12 will be changed to that of Fig. 13. The force on the armature wires is reversed, and is now in the direction of the rotation, instead of against it as in the dynamo; consequently the armature will rotate in the direction of its rotation as a dynamo. The reversal of the current through the armature, and not through the field, is shown in Fig. 14.

This property is of considerable importance when shunt dynamos are operated in parallel. If reduced speed should cause the E.M.F. of any machine to fall slightly below the line E.M.F., the armature merely continues to revolve in the same direction as a motor, and no harm is done.

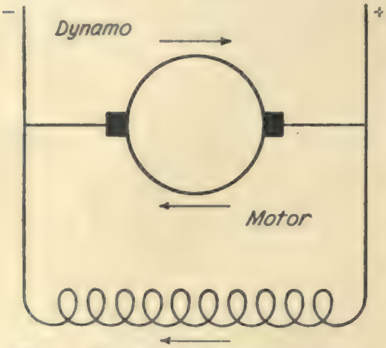


Fig. 14. Direction of Current in Shunt Dynamo and Motor.

To convert a shunt dynamo into a motor, therefore, if the direction of rotation is to remain the same, no change whatever is necessary. A starting rheostat must be added, but the machine itself needs no alteration.

The Starting Resistance. Very small motors are started by simply closing the switch that connects them to the line. No further apparatus is necessary, especially if they are series-wound, as is frequently the case to save the expense of a fine-wire shunt winding. For motors larger than about one-quarter of one horse-power, at full speed, the counter-E.M.F. prevents the current from exceeding safe values; but at starting, e is of course zero; and since R is always very small, the rush of current that would take place on throwing the full line voltage upon the motionless armature would blow out all the fuses, or might damage the armature or even the line itself. Hence it becomes necessary to insert a resistance temporarily in the armature circuit, cutting it out gradually as the speed rises. Such a resistance is called a *starting rheostat* or *starting box.*

The diminution of current through the armature as the speed increases may be easily shown by putting an incandescent lamp of about 50 candle-power in series with the armature of a small motor. Fan motors are usually series-wound; and with such it is enough to put the lamp anywhere in the circuit between the motor and the line. When the switch is closed, the lamp burns brightly for a moment and then grows dim as the armature speeds up, showing that under these conditions the starting current is much greater than the running current. The resistance of such small motors is high enough to prevent damage to the motor during the two or three seconds required to come to full speed, even though no starting resistance is used.

The starting box itself consists mainly of a resistance divided into small sections and arranged with suitable contacts so that by moving the arm of a switch the sections can be cut out one after another. At full speed, the entire resistance is cut out, and the full line E.M.F. is applied to the armature terminals. The resistance itself is made of iron wire or ribbon, wound upon asbestos-insulated tubes or strips, or embedded in insulating enamel.

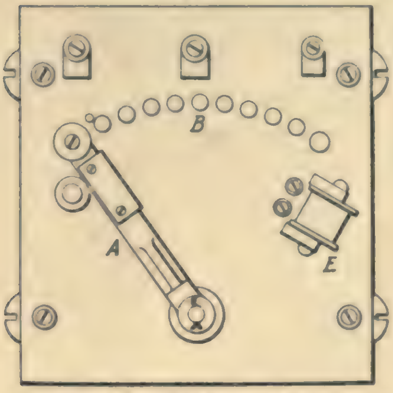


Fig. 15. Face of Starting Box.

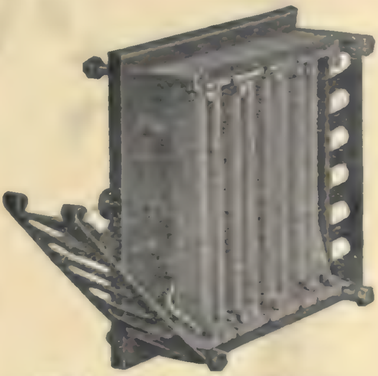


Fig. 16. Interior of Starting Box. Westinghouse Electric & Manufacturing Company, Pittsburg, Pa.

The face of such a rheostat has the general appearance shown in Fig. 15, which shows the movable switch arm *A*, the row of contact studs *B*, and a small magnet *E* whose function will be explained later. The interior of a rheostat is illustrated in Fig. 16. One side and the bottom of the box are shown removed for inspection of the resistance coils or for repairs.

When the motor is of 50 horse-power or over, the sparking that always occurs at the contact-studs soon burns them and causes trouble, and the form of rheostat shown in Fig. 15 is being superseded by a type in which the sections of the resistance are cut out by separate switches. One such form is shown in Fig. 17. The cut represents a multiple-switch starter for a 500-horse-power, 220-volt motor.

The first switch on the left is held closed by an electromagnet through which the field current passes; and the other switches are held by latches. Each switch has upon it a metal plate which prevents closing it until the switch at its left has been closed; and the interlocking mechanism thus obtained prevents a careless operator from closing the switches in the wrong order. When the current is cut off, the switch on the left is opened automatically by a spring, and this frees the switch next to it; this opens in turn; and so on until all have opened, when the apparatus is ready for starting the motor again.

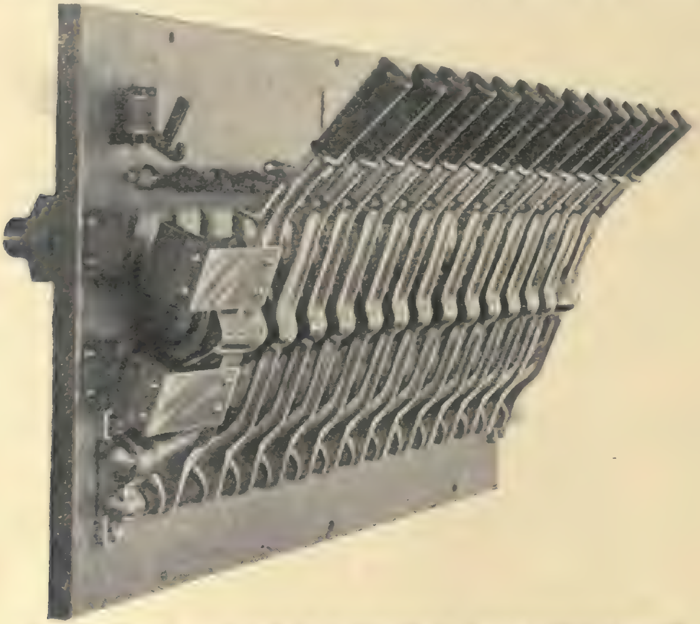


Fig. 17. Front of Multiple Switch Motor Starter, with Automatic Release. Cutler-Hammer Manufacturing Company, Milwaukee, Wis.

In starting motor-generator sets, rotary converters, and other apparatus where the starting current is only a small fraction of the running current, it is desirable to cut out the entire starting mechanism after full speed is attained. In such cases a simpler starting device is often used, of relatively small capacity and without automatic attachments. One form of such starting device is shown in Fig. 18. The picture shows clearly the way in which the steps of the resistance are cut out as the switch-blade is slowly pushed home. This switch is placed on the general switchboard of the apparatus, and the resistance mounted separately.

The maximum resistance R of the starting rheostat is determined by the equation $R = \frac{E}{I}$, where I is the current required to start the motor. Frequently motors must start under load, and the necessary starting current is considerably greater than the normal full-load running current—sometimes two or three times as much. Any good motor will safely endure this overload for the 15 or 30 seconds required to come up to speed; and many starting rheostats are designed to carry for this time a 50 per cent excess over the full-load motor current. But when a greater starting current than this is needed, or when it is desirable to allow the motor a minute or more in which to come up to speed, the ordinary starting rheostat is liable to overheat, and one of larger size must be installed. With a box designed to start the motor under load, the speed will rise rather quickly if the motor is not loaded; but this does no harm if the current is not excessive.

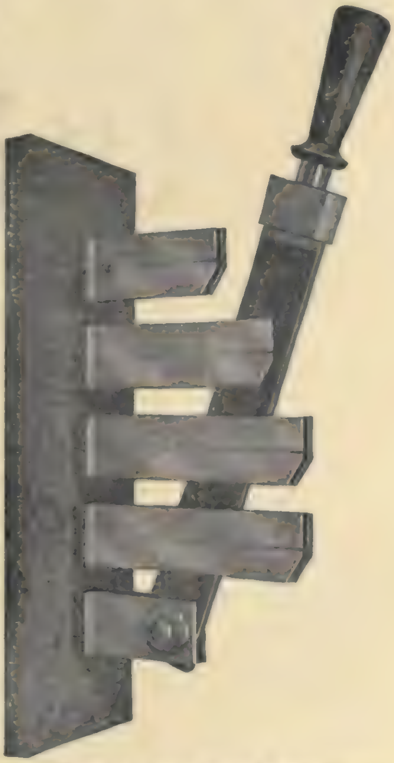


Fig. 18. Multi-Point Switch.
Westinghouse Electric & Manufacturing Company, Pittsburg, Pa.

Electrical Connections of Shunt Motor. Fig. 19 represents perhaps the simplest method of wiring a shunt motor and starting rheostat on constant-potential mains. From the line, the wires lead through a fuse-block F and a double-pole switch S. If the motor is a large one, a circuit-breaker is better than fuses. On tracing out the connections, it will be seen that when the switch S is closed the current flows through the motor fields. With the rheostat arm a in the position shown, no current flows through the armature; but on moving the arm to the first contact, the armature circuit is closed through the resistance *R*, which is gradually cut out as the handle is moved to the left. Opening the main switch cuts off the line current, but leaves the field connected across the armature terminals, as in a dynamo; so that, as the motor comes to rest, the fields die down gradually without the destructive flash that would occur if the field circuit were opened suddenly while the magnets are excited. For this reason the field circuit should not be opened first.

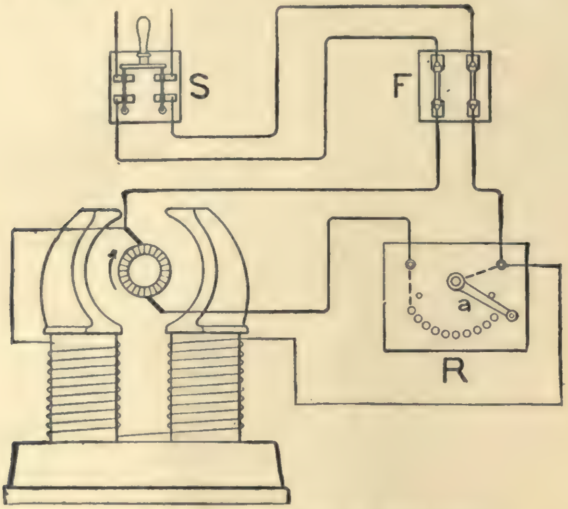


Fig. 19. Wiring Connections of Shunt Motor.

When the armature has come nearly to rest, the rheostat arm is restored to the original position, and the motor is ready for starting again.

Automatic Release. The preceding diagram has been drawn to reduce the principle to its lowest terms and to keep the drawing clear; but in practice the simple rheostat shown is seldom used. After the motor is shut down by opening the main switch, the rheostat lever must be moved back by hand, to the starting position; and this is an operating detail that is very easily forgotten. Consequently, when the motor is to be started again, the position of the arm may not be noticed, and damage may be done by closing the switch with no resistance in the armature circuit. Furthermore, the power supply may be cut off and the line may become "dead" while the motor is running, whereupon the motor stops of itself with the rheostat arm in the running position as before. It is therefore the almost universal custom to install rheostats which are arranged to allow the arm to fly back automatically to the off position whenever the power is shut off from the motor. One method of accomplishing this is to connect the auxiliary or retaining magnet shown in Fig. 15 in series with the motor fields, the rheostat arm being provided with a spring tending to throw it back into the off position. When in the running position, as shown, the iron arm is held by the attraction of the magnet against the force of the spring; but when the motor loses its field, the magnet loses its power, and the spring carries the arm back into the off position. The retaining magnet is placed in series with the field rather than the armature, because it is thus independent of the load on the machine, and in addition affords protec-

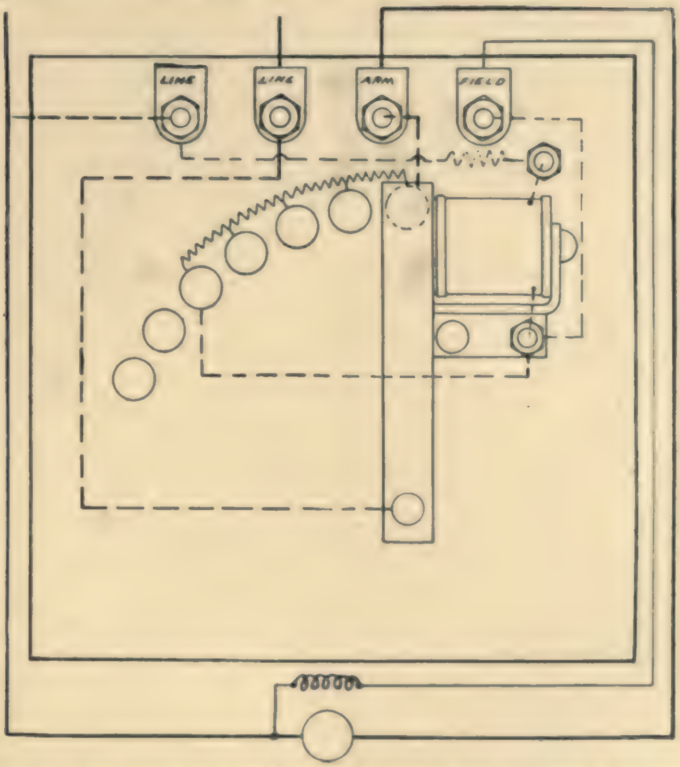


Fig. 20. Connections of Motor-Starting Rheostat with No-Voltage Release.

tion in case the field circuit should be broken while running, thus leaving the armature without any counter-E.M.F.

There are other ways of accomplishing the same result. The one shown in Fig. 20 represents a method of connection employed by the General Electric Company. Here, as may be seen by tracing out the connections, the retaining magnet is connected across the armature terminals. When the line circuit is opened, the rheostat arm is held by the current generated in the magnet-coils by the armature E. M. F., until, as the armature slows down, the magnet weakens, and the spring pulls the arm over into the starting position.

Wiring Connections. Figs. 15 and 19 are typical. The ordinary starting rheostat has three terminals, which are usually marked *Line, Armature,* and *Field* or *Shunt Field.* There are four terminals on the motor (*a, b, c, d,* Fig. 21)—two for the armature and two for the field; but one armature and one field terminal are always at the same potential and may therefore be connected, leaving three separate terminals *c′, a,* and *b* on the motor, which may be called *Line, Armature,* and *Field,* respectively.

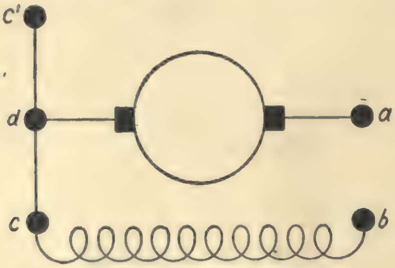


Fig. 21. Motor Field and Armature Terminals.

If the rheostat terminals are marked as above, the wiring of a shunt motor then becomes a simple matter. After putting in the fuses and double-pole switch, first run a wire from one pole of the switch to the rheostat terminal marked *Line.* Run a second wire from the *Armature* terminal of the rheostat to the free terminal *a* of the motor armature, and a third wire from the *Field* terminal of the rheostat to the free terminal *b* of the motor field. This wire, which carries only the field current, may often be made smaller than the others. Finally, run a wire from *c′*, the common terminal of the motor field and armature, back to the other pole of the switch.

A common mistake in wiring consists in interchanging the *Line* and *Armature* wires at the starting box. On the first contact-stud, this puts the field across the brushes and therefore in parallel with the armature, both being in series with the starting resistance. Hence, since most of the line E.M.F. is expended in the resistance, there is very little across the terminals of the field winding and the armature; and the field is consequently so weak that the motor may not develop sufficient starting torque unless the current is large enough to injure the starting box. This is one of the first places to look for the trouble, if a motor does not start properly when first installed.

There are several methods of arranging the connections inside the starting box itself, as shown in Fig. 22, in which the retaining magnet *E* is drawn outside the box for clearness. It will be noticed that the only difference is in the connection of the field circuit. In the upper diagram, closing the switch establishes the field circuit; while in the lower diagram, no current flows until the rheostat arm is moved to the first stud. In the lower diagram the starting resistance is always in the field circuit; but its resistance is so small compared with that of the field coils that its effect is not noticed. By an auxiliary contact *m*, the resistance is sometimes cut out entirely. The little magnet *E* takes only a few watts, and is without effect on the operation of the motor.

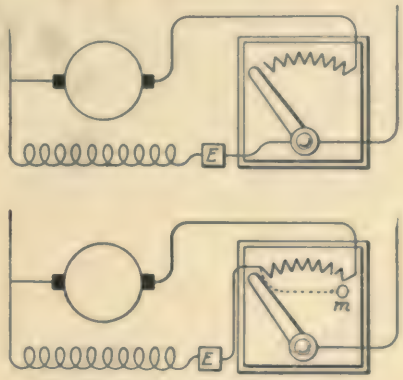


Fig. 22. Starting-Box Connections.

Overload Release. This is a useful addition to the starting box, for the purpose of cutting the motor out of circuit when the armature current becomes excessive, without relying on the fuses or circuit-breaker. It consists of a second electromagnet through which the armature current passes, mounted on the face of the starting box, and provided with a movable armature which hangs down like a hinge below the magnet-poles. When the current exceeds the proper strength, the armature is lifted by the attraction of the magnet and presses against little contact-pins, short-circuiting the release magnet holding the rheostat arm, whereupon the arm at once flies back to the off position.

This device is not intended to be used as a substitute for the fuses, but is adjustable and useful for taking care of overloads not exceeding about 50 per cent. Heavier fuses may then be used, giving the necessary protection but saving the annoyance of frequently blown fuses. Fig. 23 shows the connections of a rheostat equipped with an overload release of this type.

OPERATION OF MOTOR

To Start the Motor. In starting the motor, the following directions are to be observed:

1. Close the main switch. According to the method of connection, as shown in Fig. 22, this will either establish the current through the field, or will merely bring the line voltage up to the starting box.

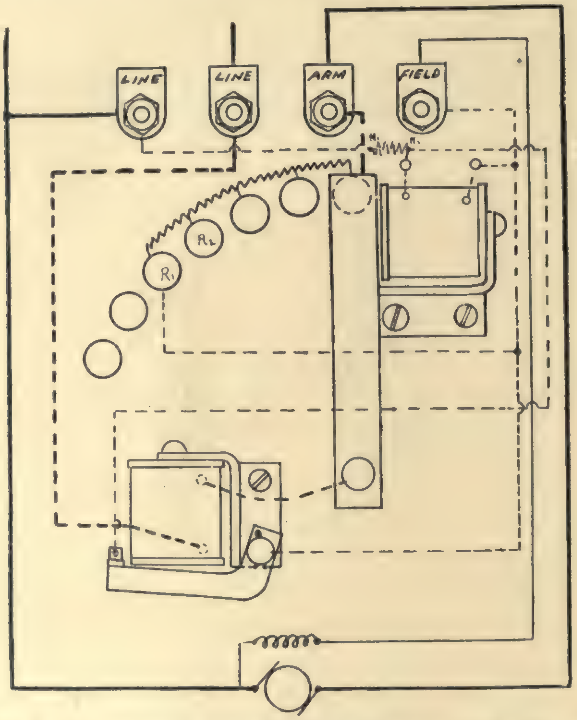


Fig. 23. Connections of Motor-Starting Rheostat with No-Voltage and Overload Release.
General Electric Company, Schenectady, N. Y.

2. Move the rheostat lever to the first contact, and hold it there for one or two seconds.

3. Move the lever to the second stud, and hold it there for about one second; and so on, until all the studs have been passed

over and the resistance is short-circuited. The lever should then be firmly held by the retaining magnet. The entire operation should not consume more than 15 to 30 seconds.

If the motor does not start when the lever is on the third stud, open the main switch, and look for the trouble. It may be due to one or another of the following causes:

1. Overload.
2. An open circuit somewhere.
3. A short circuit somewhere.
4. Wrong connections.

No cause of motor trouble is more common than simple overloading. Always at the time of installation, and occasionally thereafter, an ammeter should be connected into the motor circuit, and its reading compared with the rated current of the motor. Motors are designed to do their work with but little attention. They frequently get none at all; belt, commutator, and bearings are neglected; additional machinery is put into the shop and operated from the original motor; and so on—with the inevitable result of overload.

The methods of locating troubles and remedying them, and of caring for dynamo-electric machinery in general, are matters of such importance that their full discussion requires treatment in a separate paper.

To Stop the Motor. Open the main switch. The motor will run for a little time by its own momentum, and the retaining magnet will not allow the rheostat arm to fly back until the armature has slowed down considerably. If the contact-studs are dirty, the lever may not move readily over them; and if it does not fly back sharply, they should be cleaned, and the spring on the lever adjusted if necessary.

Reversing Direction of Rotation. Most motors are now built with radial brushes, and may rotate equally well in either direction. To reverse the rotation, it is necessary to change the direction either of the field or of the armature current, but not of both, since the double reversal would be equivalent to turning Fig. 3 over twice, leaving the force upon the armature, and consequently the rotation, in the same direction as before.

To allow easy connection for rotation in either direction, some motors are provided with separate field and armature terminals, as shown in Fig. 24. The direction of the armature current can then be reversed by changing the connections as shown.

In motors which are to be reversed while in operation, the armature connections are the ones changed, because this causes less severe strains on the insulation than reversing the highly inductive field circuit. If the motor is merely to be reversed once for all, the brushes should be shifted to the proper lead on the other side of the no-load position; but if it must run in either direction while at work, of course no lead can be given to the brushes, and they must be fixed permanently in the no-load position.

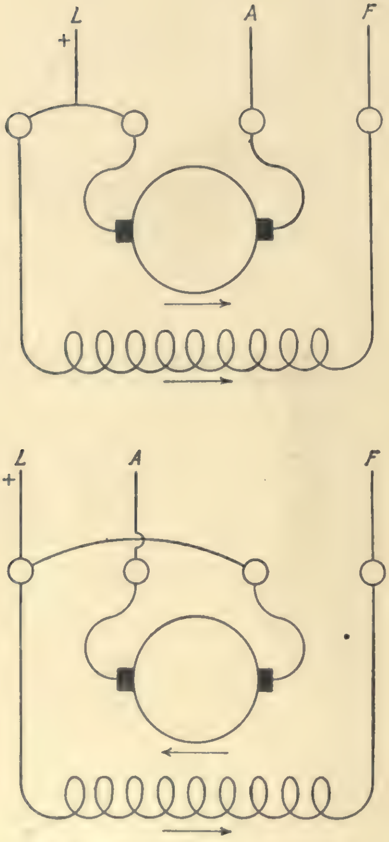


Fig. 24. Connections for Reversing a Motor.

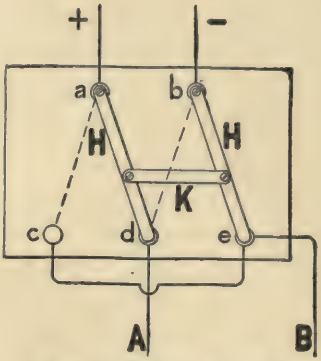


Fig. 25. Reversing Switch.

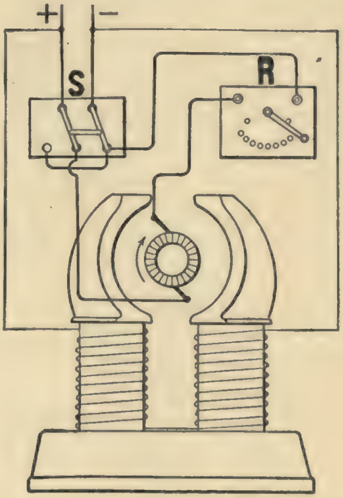


Fig. 26. Connections of Reversing Switch.

A motor should never be reversed while running, except for the most necessary reasons, and then not until the full resistance is inserted in the armature circuit. For with the line E.M.F. reversed, the counter-E.M.F. of the armature is for a moment added to that of the line, and the excessive current that flows brings the armature to a stop with a severe jolt that is very likely to cause damage.

Fig. 25 shows one form of reversing switch; and Fig. 26, the manner of its connection into the armature circuit. In Fig. 25, *H* and *H* are brass bars pivoted at *a* and *b*, and connected by a fiber cross-piece *K*. As shown, they are in contact with the studs *d* and *e*. When *K* is moved so as to bring the bars on the studs *c* and *d*, as shown by the dotted lines, it is easy to see that the current will be reversed in the circuit *AB*.

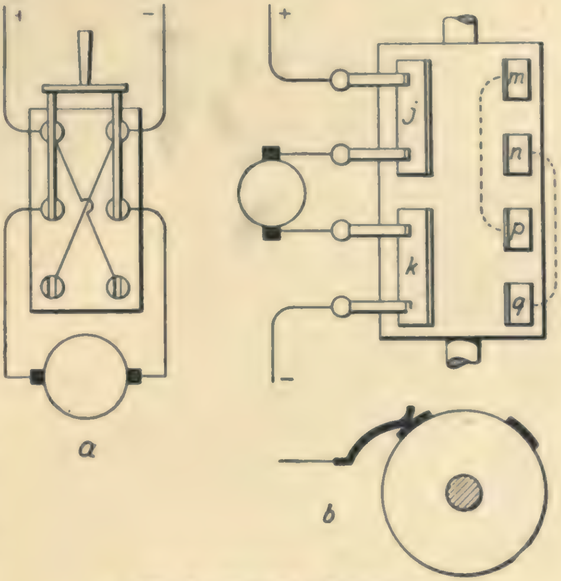


Fig. 27. Reversing Switches.
a—Knife Switch; *b*—Cylinder Switch.

Fig. 27 shows, at *a*, a simple and satisfactory reversing switch made by cross-connecting the clips of an ordinary double-pole, double-throw knife switch. The line circuit is connected to the clips; the circuit to be reversed is connected to the switch-blades; and simply throwing the switch up or down accomplishes the result.

At *b* in Fig. 27 is shown the principle of cylinder construction which, in a more elaborate form, is much used for speed controllers. In the diagram, an insulating cylinder carries two rows of contact-blocks against which spring contact-fingers press, connected to the various terminals of the motor circuit. When the cylinder is turned to bring the blocks *j* and *k* into contact with the fingers, the current will flow downwards through the motor armature; and with the blocks *m*, *n*, *p*, and *q* in contact, the current will flow upwards. It is obvious that this arrangement may be extended to execute much more complicated combinations of circuits, by the use of more fingers and more rows of contact-blocks; and in a highly developed form it is widely used for controlling the motors of street-railways.

Automatic Starters. The control of a motor from a distance usually involves the necessity of a *self-starting apparatus*, by which all the motions of the starting rheostat are automatically performed on closing the distant control switch. The movement of the rheostat arm is effected by a solenoid, and the rate of its motion is governed by a dashpot filled with oil. A valve in the dashpot allows the total time of the motion to be varied as required; or thick or thin oil may be used for the same purpose. Perhaps the most common instance of this kind of service is the supply of open tanks with water, and closed reservoirs with compressed air. In the first case, a float switch starts the pump when the water falls below a certain level, and stops it when the tank is full; in the second case, the pressure must be kept within certain limits, and a diaphragm valve makes and breaks the control circuit.

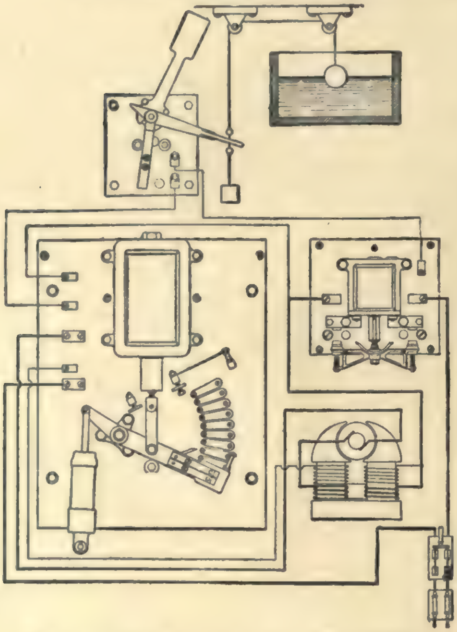


Fig. 28. Self-Starter Used with Motor-Driven Pump.
Cutler-Hammer Mfg. Co., Milwaukee, Wis.

Fig. 28 shows a self-starter operated by a float switch. This switch, when closed, energizes the solenoid of the main switch shown above the motor in the diagram. Closing the main switch also energizes the solenoid on the rheostat arm, and the arm rises, thus starting the motor. At the end of its travel, the arm breaks a contact, and by so doing inserts an incandescent lamp in the circuit of the solenoid, preventing overheating, a small current being enough to hold the arm in place. The motion of the arm also inserts a lamp resistance in the circuit of the main switch solenoid, as a safety device. For if the main switch is opened, and then closed before the rheostat arm has inserted all the resistance into the motor circuit, the rush of current might blow the fuses; but the lamp is short-circuited only in the off position of the arm; and only under these conditions is the current strong enough to lift the plunger and close the switch.

Reversing Starters. Lathes and other machine tools must often run backwards as well as forwards. Fig. 29 shows a starting apparatus designed to meet this condition. It is in effect a pair of starting rheostats, designed to bring the motor to full speed in either direction. When the handle is in the middle position, the motor is cut out of circuit; and moving the handle to one side or the other starts the motor forward or backward correspondingly.

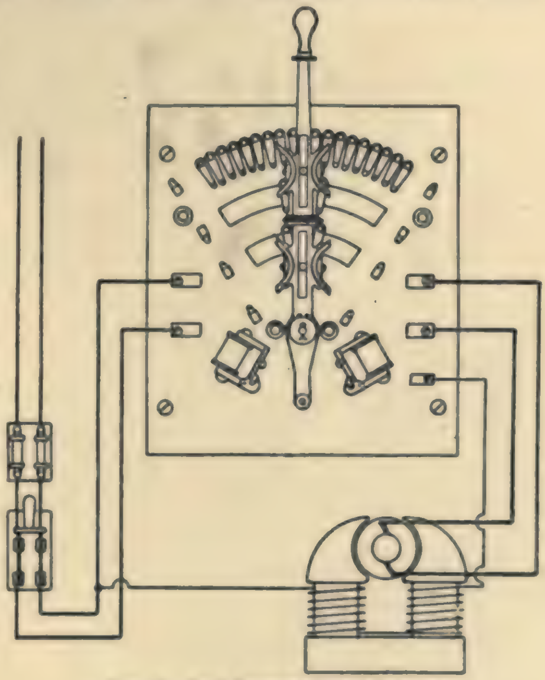


Fig. 29. Full Reverse Motor Starter.
Cutler-Hammer Mfg. Co., Milwaukee, Wis.

SPEED CONTROL OF SHUNT MOTORS

Varying E.M.F. at Brushes. A wide range of speed is easily obtained by simply inserting a suitable resistance in the armature circuit, as indicated by R, Fig. 30, leaving the field circuit FF unchanged. The amount of resistance inserted in order to obtain the desired speed and torque can be calculated in several ways.

Example. A certain 110-volt shunt motor takes 75 amperes at full load, at a speed of 700 revolutions per minute. What resistance must be put in series with the armature to obtain half-speed at two-thirds of the full-load torque?

Solution. In Equation 7 (page 17),

$$s = \frac{E - IR}{k\,f\,z},$$

R includes not only the armature resistance, but any other resistance that may be in series with it. At full speed there is no resistance in the armature circuit, except that of the armature itself; and this is negligible in problems like these, so that in this case we may write:

$$s = \frac{E - 0}{k\,f\,z} = 700 = \frac{110}{k\,f\,z}\text{; whence } k\,f\,z = 0.157.$$

The torque at the new speed will obviously require two-thirds of 75 amperes, or 50 amperes. Therefore, using Equation 7 again,

$$s = \frac{E - IR}{k\,f\,z} = 350 = \frac{110 - 50\,R}{0.157}\text{; whence } R = 1.1 \text{ ohms, nearly.}$$

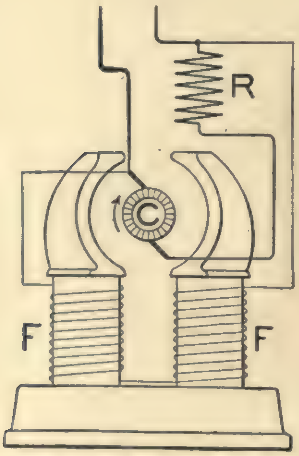


Fig. 30. Speed Control by Resistance in Armature Circuit.

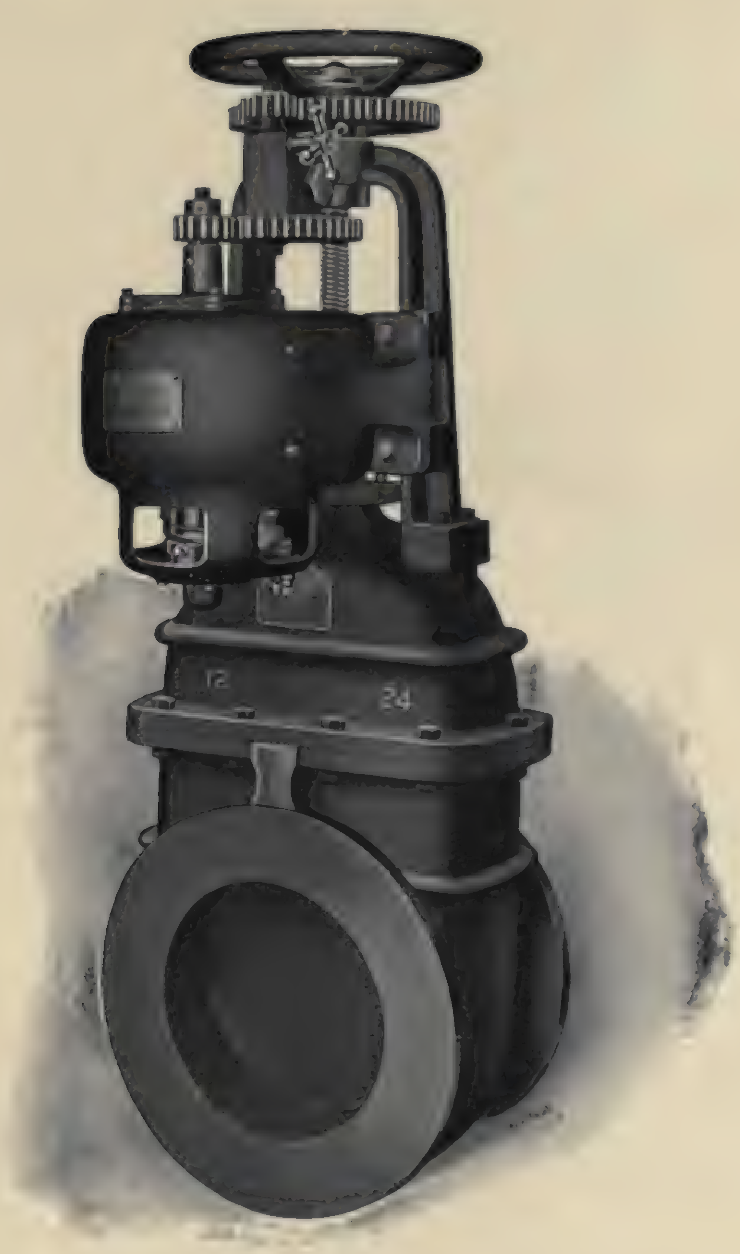
For a more exact solution, the armature resistance should be known; but the above method is quite accurate enough for all ordinary cases.

The above method of speed control has the advantage of simplicity, cheapness, and wide range. It is objectionable, however, when the load is fluctuating, for the E.M.F. at the armature terminals, and hence the speed, depend upon the IR loss in the resistance; and IR of course varies with every change in I. Thus, whenever the load increases, the speed will decrease, and conversely; and this is objectionable in many classes of work. A second objection is that the voltage taken up in the resistance represents just so much power wasted, the loss in watts being simply I^2R. With a large motor, this loss may be a somewhat expensive matter; with a small one, the simplicity and convenience largely offset the cost of operation.

EXAMPLES FOR PRACTICE

1. The full-load current of a 250-volt motor is 20 amperes, and the speed 800 revolutions per minute. What resistance is required in series with the armature, to give $\frac{3}{4}$-speed with $\frac{1}{2}$-full-load torque?

Ans. 6.25 ohms.



ELECTRICALLY OPERATED GATE VALVE.

With Direct-Current Motor.

Chapman Valve Manufacturing Co.

2. What is the power loss in the resistance added to the 110-volt motor discussed above? Ans. 2,750 watts.

3. What fraction of the power supplied to the 220-volt motor above discussed is wasted in the added resistance? Ans. 25 per cent.

It is important to note that for the above purposes the starting rheostat must never be used. The specific heat of the materials of the rheostat is utilized to keep its temperature within safe limits during the brief time required for starting. The box is not large enough to dissipate much heat, and, if used as a speed controller, would burn out in a very short time. Resistances used to dissipate much energy continuously, must have liberally proportioned surfaces and free ventilation. Small ones are usually made of iron wire, larger ones of iron ribbon, wound on asbestos supports to expose as much surface as possible to the air; very large ones are made of zigzag strips of cast iron, called *grids*. Fig. 31 shows single grids of various sizes. As many elements as needed are assembled in iron frames.

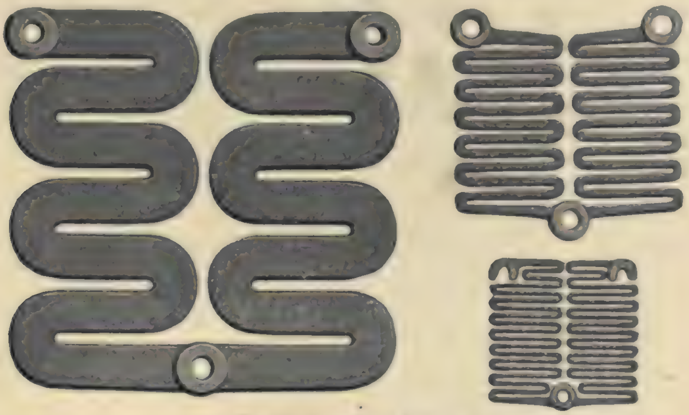


Fig. 31. Standard Grids.
Westinghouse Electric & Manufacturing Company, Pittsburg, Pa.

Speed Control by Varying Field. This method is very simple in principle, and wastes but little energy in the controlling resistance. By varying a resistance in series with the field windings of a shunt motor, the field, and hence the speed, are controllable to a certain extent. The advantage of this method of control is in its simplicity, and in the fact that since the field current is small, there is but little energy wasted and little heat to dissipate from the rheostat. Further, the speed is adjustable by small steps. The disadvantage of the method arises from the fact that the field must not be weakened below the point of satisfactory commutation. This, with an ordinary motor, limits the speed variation to about 25 per cent, or perhaps 30 per cent. If a greater range than this is required, a larger and heavier field-magnet must be provided; for example, for a 2 to 1 variation, a 15-horse-power frame should be used for a 10-horse-power motor, while a 3 to 1 variation requires a 20-horse-power frame for a 10-horse-power motor, with other sizes in proportion. This, of course, means a motor of large size in proportion to its output. The torque diminishes with the weakened field, and this is just compensated by the increased speed, so that the motor runs with practically constant horse-power output. For

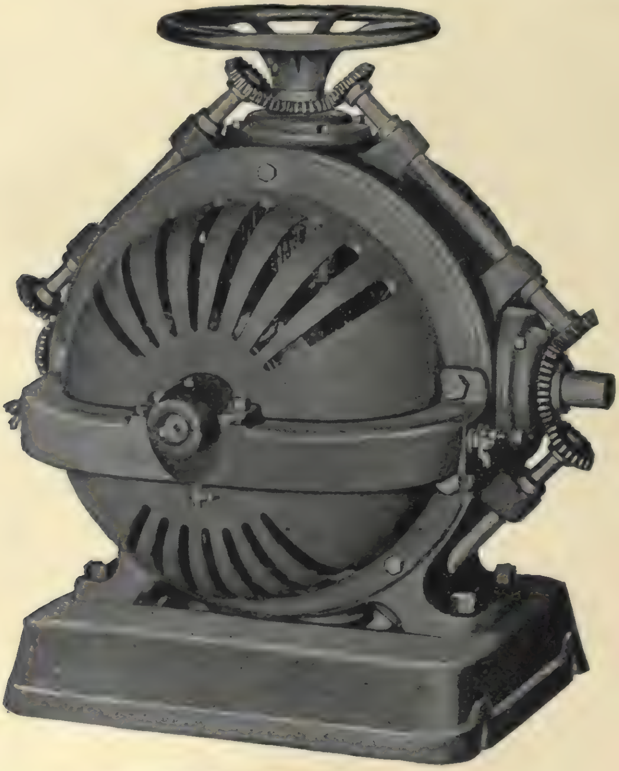


Fig. 32. Variable-Speed Motor.
Stow Manufacturing Co., Binghamton, N. Y.

still greater speed variations, special constructions are used, which will be described later. Fig. 43 (page 52) shows an adjustable-speed motor giving a 3 to 1 variation in speed by variation of field resistance.

Apart from the extra size of the motor, speed control by this system is very satisfactory where conditions do not warrant the installation of a multiple-voltage system.

Control by Varying Magnetic Reluctance. If the reluctance of the magnetic circuit is varied, the field strength will vary though the field current is kept constant. Advantage of this is taken in the motor illustrated in Fig. 32. In this machine the field cores and poles are hollow and provided with iron plungers, which can be moved toward the armature or away from it by a hand-wheel operating suitable gearing. The advantage of this construction is that, when the plungers are withdrawn, the magnetic flux is obliged to enter the armature through the edges of the pole-pieces; and hence, even with the weakest total field, the actual distribution is always such as to give proper commutation. Moreover, the armature reaction is reduced with weak fields, because iron is removed from the path of the cross-flux, and this also assists commutation. A 3 to 1 speed variation is obtained.

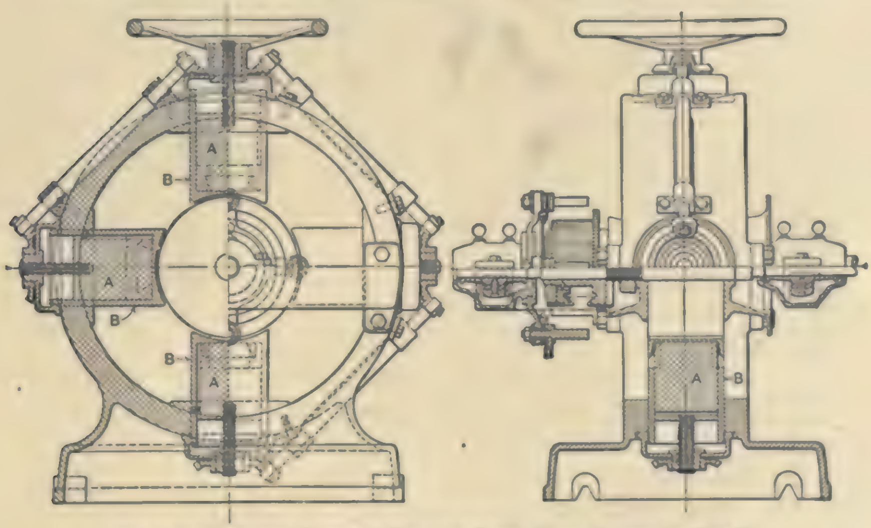


Fig. 32A. Sectional Views of Variable-Speed Motor Shown in Fig. 32.

Control by Varying Line E.M.F. This will be discussed later, under the heading *Multi-Voltage Systems.*

Combination Methods. It is evident that the preceding methods of speed control are largely independent of one another, and may therefore be used in combination, giving a wide range of speed; and several combinations are discussed in the following pages. They are applicable to shunt and series motors alike. When a number of running speeds forward and backward are required, as in hoisting machinery and machine tools, and the stops and starts are frequent, as in elevator service, the controlling apparatus must be of the most substantial construction, and is often very elaborate.

SERIES MOTORS

As with series dynamos, the armature and field windings of these machines are in series, and the same current therefore passes through both. They are always used upon electric railways, and in general for operating hoisting and mill machinery, where a strong starting torque is required without the necessity of constant speed. Like shunt motors, they are practically always operated on constant-potential circuits.

Direction of Rotation. In considering the direction of rotation of a shunt dynamo used as a motor (page 23), it was noted that the field and the direction of rotation remain unchanged when the armature current reverses its direction, and the dynamo becomes a motor; but in the case of a series dynamo used under like conditions, the reversal of the current reverses the field as well, and hence the armature tends to rotate in the opposite direction. If, therefore, a series dynamo were feeding a constant-potential circuit, and its E.M.F. fell below that of the line for any reason, its rotation would be reversed and the machine would be injured.

A series motor will run in the same direction, no matter which direction the current takes through it; for reversing the armature current reverses the field as well, and hence leaves the rotation unchanged. To reverse the rotation, it is necessary to reverse the relation of the armature and field currents, and this is usually done by interchanging the armature terminals.

Speed and Torque Curves. When a series motor running at a given speed on constant-potential mains has an additional load put upon it, the armature slows down, the counter-E.M.F. decreases, and more current flows from the line. But since this current passes through the field-coils, the field strength will increase, and this will further reduce the speed, while the torque will increase enough to take care of the increased load. Throwing off the load will allow the armature to speed up, and this will increase the counter-E.M.F., reducing the current, which in turn reduces the field strength and still further increases the speed, until the power delivered and the losses together equal the power taken from the line. Hence the series motor has a different speed for every load. If the strength of the field were proportional to the current, the speed curve would be a straight line; but as the current increases, the magnets are more nearly saturated, and the speed decreases less rapidly toward full load. The speed curve takes, in general, the form shown in Fig. 33, which is from a 50-horse-power railway motor. By having so many turns of wire on the field-magnets that they are well saturated with only a part of the full-load current, the speed variations in the neighborhood of full load are much reduced.

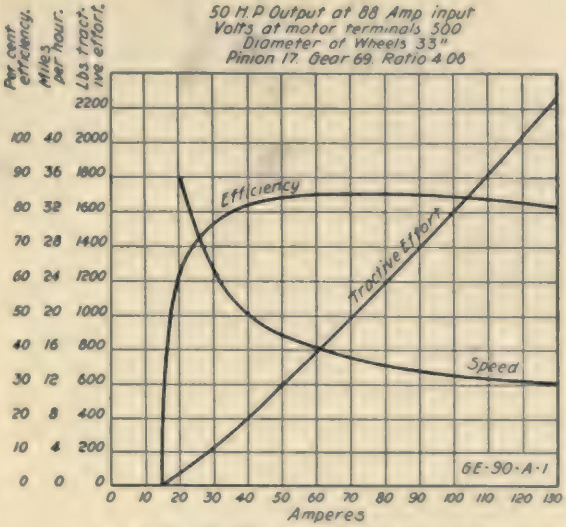


Fig. 33. Speed, Torque, and Efficiency Curves of a Railway Motor.

A valuable property of the series motor is the increase of torque in a greater ratio than the increase of current, due to the strengthening of the field at the same time. This is shown by the curve marked "Tractive Effort" in Fig. 33; for a shunt motor, this curve would be a straight line. Hence the torque of the series motor is large when starting under load, and this makes it especially valuable for railway and other service where the starting duty is severe.

When the load is removed entirely from a series motor, the diminution of the current, and consequent weakening of the field, are likely to cause excessive and often dangerous speeds, so that it is necessary to provide some safety device for cutting off the current at high speeds, unless the conditions are such that the motor cannot be wholly freed from its load, as in the case of street-cars. Very small motors, such as fan motors, are series-wound; but their normal running current is so small that they cannot take enough power from the line to injure themselves, even when running free.

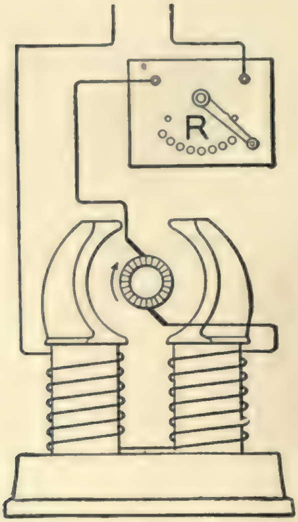


Fig. 34. Wiring Connections of a Series Motor.

Starting Rheostat. The same general principles apply to starting both shunt and series motors; but since there is only one circuit in the series motor, the wiring is simpler. The connections are as in Fig. 34, in which, however, the switch and fuses are not shown. The resistance of the field windings is always in circuit; and this, together with its highly inductive character, helps to cut down the rush of current at starting. The little magnet *E* of the automatic release (Fig. 22) is connected through a resistance across the motor terminals.

SPEED CONTROL OF SERIES MOTORS

Varying the E. M.F. at Armature Terminals. As in the case of shunt motors, all three methods of speed control are practicable, and may be used separately or in combination. With a single motor, varying the E.M.F. at the armature is most easily accomplished by a resistance in series with the motor. The connections are as in Fig. 34, where *R* may represent either a starting rheostat or a speed-controlling resistance, though of course neither piece of apparatus can be used for the purposes of the other unless specially constructed. Controlling the speed by varying the strength of the field is accomplished either by shunting the field windings so that part of the current is diverted through the shunt, or, in some cases, by short-circuiting a part of the field winding, thus reducing the effective number of turns in the coils. Motors have also been used in which the field-coils were connected in various series-parallel combinations.

Railway Motors. The most important application of the series motor is on the electric railway, the equipment being generally two motors per car. The starting rheostat is specially designed to serve as a speed-regulating resistance as well, and the various armature and field combinations are made by a controller, built like an elaborated form of that shown at *b* in Fig. 27. At starting, the controller connects both motors and a resistance in series, and the resistance is gradually cut out, leaving the motors in series across the line, each receiving one-half of the line voltage and hence running at half-speed. The next position of the controller handle shunts the field or short-circuits a part of the field winding, giving an increase in speed. Further movement of the handle removes the shunt, and connects the motors in parallel, but with a resistance in series with the pair. This is again gradually cut out until each motor receives the full line voltage across its terminals. Finally, the fields are again shunted, and the car runs at its highest speed.

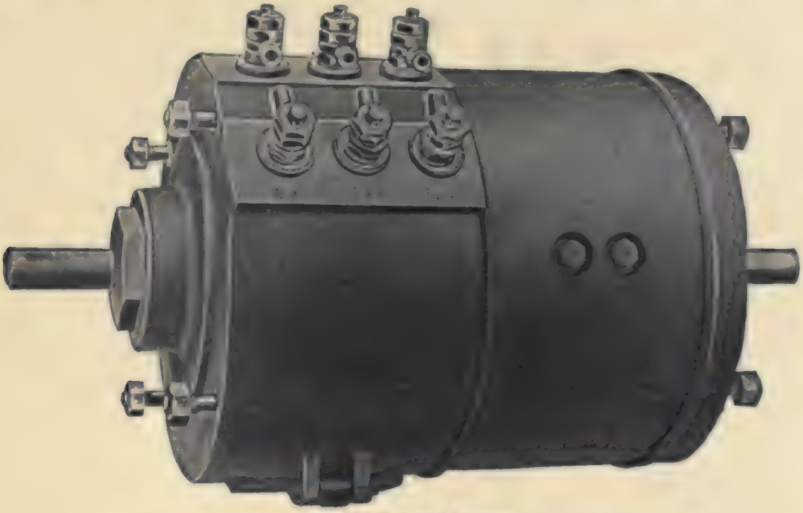


Fig. 35. Vehicle Motor.
Westinghouse Electric & Manufacturing Company, Pittsburg, Pa.

There are slight variations from this program, depending somewhat on the service the motors are called upon to perform. But these details of the subject of railway working are given special discussion in a separate paper.

Automobile Motors. These are series-wound, usually for operation at 40 to 80 volts, requiring 20 to 40 cells of battery respectively. A ball-bearing vehicle motor is shown in Fig. 35. The requirements for such motors are slow speed, light weight, high torque, complete mechanical protection, liberal overload capacity, and as good an efficiency as can be secured consistently with the above requirements. When two motors are used on the same vehicle, the controller may first connect the motors in series, and the halves of the battery in parallel, other changes following until the motors are in parallel across the full battery voltage, with weakened fields. No rheostat is necessary, as the voltages are low, and the total power delivered usually small.

COMPOUND MOTORS

A reversed compound dynamo becomes a differential motor. Fig. 36 represents a compound dynamo D supplying current to a similar machine M used as a motor. It is clear that the current through the series coil of the motor is reversed; and therefore opposes the magnetizing effect of the shunt current, so that the field is weaker than if the shunt were used alone. Furthermore, the motor field is progressively weakened as the armature current increases, and this tends to increase the speed; while the speed of a plain shunt motor under like conditions would decrease. Hence, by suitably designing the series winding, it is possible to obtain a motor whose speed throughout its whole range of load varies very little. This advantage was early recognized; but at the time the speed of ordinary shunt motors was sufficiently constant for most purposes, and the *differential compound motor* made little headway. For some purposes, however, particularly in the operation of textile machinery, it is very necessary to have the speed as uniform as it can be made; and the differential

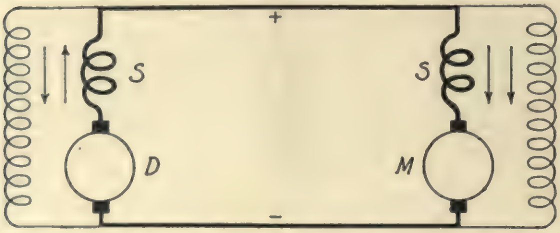


Fig. 36. Compound Dynamo Driving Compound Motor.

motor, after a period of comparative retirement, has now a wide field of usefulness.

If the current through the field is reversed, so that it assists the shunt winding instead of opposing it, the machine is called a *cumulative compound motor*, and partakes to a certain extent of the properties of both the shunt and series types, the shunt predominating. These machines are used for elevator and other service where a powerful starting torque is required, together with the general characteristics of the shunt motor. Sometimes the series field is cut out after the armature attains full speed, in which case the strong starting torque of the series motor is combined with the constant-speed property of the shunt motor.

A compound dynamo with a very strong series field will not usually run safely as a differential motor, for an overload might reduce the field so much that with the weakened torque the armature might stop entirely.

Variable-Speed Compound Motors. The success attending the the use of the *commutating pole* in generators, has led to the adoption of the same principle for motors designed for wide ranges of speed. The commutating pole is a small additional pole, placed midway between adjacent field-poles, and wound with a few turns of the series winding. Its function is to provide the necessary commutating field for the coil under the brushes, independently of the field of the main poles. Thus satisfactory commutation not only can be obtained with the brushes in a fixed position, but practically is equally good at all loads, since the strength of the pole, and hence of the commutating field, is proportional to the armature current, and this is exactly what is wanted for good commutation. Applied to motors—since commutation is practically independent of the main field—the use of the commutating pole allows the main field to be weakened much more than with the ordinary construction, and hence a much wider range of speeds is obtainable without sparking. Fig. 37 shows a motor of this type giving a speed range of 4 to 1, entirely by field control.

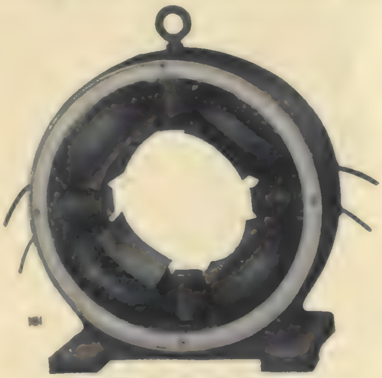


Fig. 37. Interpole Motor.
Electro-Dynamic Company, Bayonne, N. J.

MULTI-VOLTAGE SYSTEMS

When a generator is to supply only one motor, the line E.M.F. can be varied at pleasure by varying the generator E.M.F., having the generator field rheostat at the motor. This method gives any desired motor speed within a very wide range, but is obviously limited to a few special cases. The so-called *teaser* systems are in effect modifications of this principle; the E.M.F. of small motor-driven generators is added to that of the main line or subtracted from it. This particular modification of the variable line-voltage principle is useful for operating large printing presses or other machinery which must run very slowly at times under absolute control, as well as at various operating speeds.

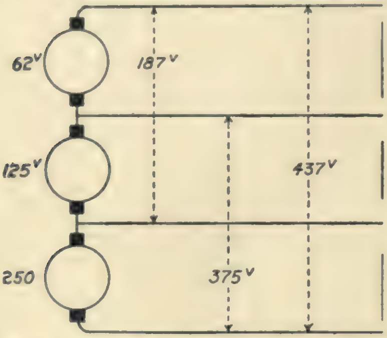


Fig. 38. H. Ward Leonard Multi-Voltage System, 1892.

The electric automobile affords an example of speed-control by varying line voltage. The batteries of the vehicle are in two sets, which are connected in parallel at starting, and then shifted to series connection at the higher speeds.

The familiar Edison three-wire system affords another illustration. In this case the fields of a 220-volt motor would be supplied from the outside wires, and the armature at either 110 or 220 volts, giving two speeds without the use of resistances.

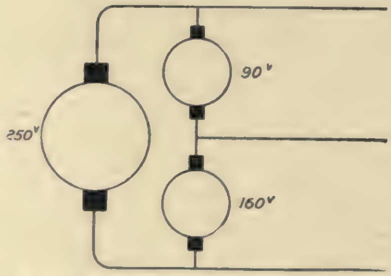


Fig. 39. Connections of Balancer Set.

By making the two sides of the system unequal in voltage, three voltages are obtained. In such a case, the lighting system of the shop, the cranes, and constant-speed motors are operated on the outside wires. A system of this kind was first brought out by Mr. H. Ward Leonard in 1892, using three generators in series and a four-wire system, obtaining the six voltages shown in Fig. 38.

The Bullock Electric Company employs a three-wire system with 90 and 160 volts, and a four-wire system with 60, 80, and 110 volts, with outside voltages of 250 in both cases. The Crocker-Wheeler Company use a four-wire system with 40, 120, and 80 volts, giving 240 volts on the outside wires. Whatever voltages may be used, it is well to have at least one of the voltages *standard*—that is, 110 to 125 volts, or 220 to 250 volts, because these are standard voltages for lamps and motors.

In practice it is found that the intermediate wires carry only a small proportion of the total load, usually not over 10 per cent. This has led to the use of a single large generator and *balancers*, which are simply smaller shunt or compound dynamos with their armatures coupled together and electrically connected in series across the outside wires. The general arrangement is shown in Fig. 39, and Fig. 40 illustrates a Bullock three-wire balancer set.

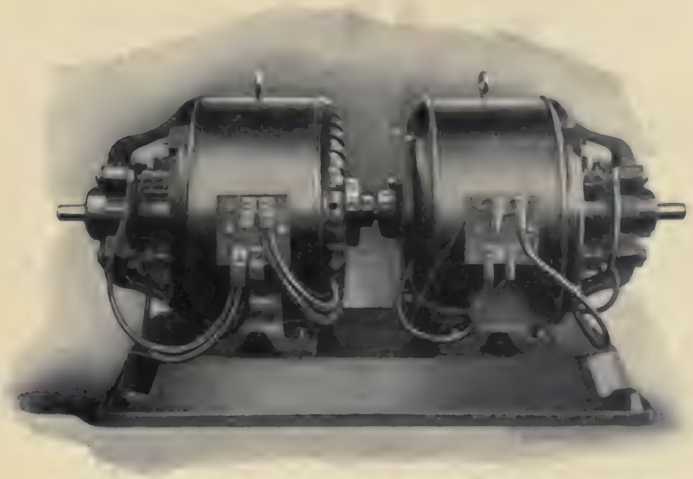


Fig. 40. Three-Wire Balancers for Bullock Multiple-Voltage System.
Allis-Chalmers Company, Milwaukee, Wis.

The action of the balancer is complex, and a full explanation is not desirable here. In general terms, however, it may be stated that when there is no current in the middle wire of a three-wire system the current through the balancer armatures is only enough to supply the running losses; but when current is drawn from either side of the system, the balancer on the other side will act as a motor, driving its companion as a generator to help furnish the required power. This is illustrated in Fig. 41, where one outer wire carries 100 amperes, the middle wire 20 amperes, and the other outer wire 80 amperes. If the balancers are equal, and there are no losses, the 20 amperes divide equally between the armatures, 10 amperes flowing downward through one as a motor to the negative main, the armature then acting as a motor driving the other machine as a generator and helping it to force the remaining 10 amperes up into the positive main again. Supposing the voltage of the main generator to be 200 volts, its output would be 90 amperes at 200 volts, or 18,000 watts. The load on the line is 80 amperes at 200 volts, and 20 amperes at 100 volts = 18,000 watts, as before.

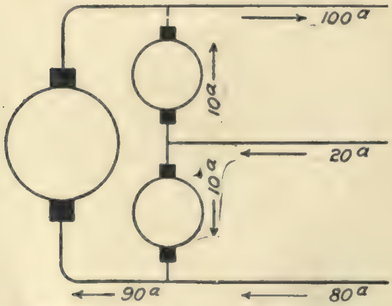


Fig. 41. Current through Balancer Set.

Of course there are always losses in the balancer armatures, so that in the arrangement shown the current through the armature acting as a motor is always greater than the current through the armature acting as a dynamo.

EXAMPLE FOR PRACTICE

If 13 amperes, instead of 10, flow through the balancer motor armature in the above example, what is the output of the main generator, and what power is delivered to the line?

Ans. 18,600 watts from the generator.
18,000 watts on the line.

This would represent 600 watts loss in the balancers, which is, however, much less than would be required to operate the second generator of an ordinary three-wire system.

The size of the balancers is determined by the maximum unbalanced load. On a three-wire system it should be large enough to operate the largest individual motor running alone on either voltage. For example, suppose we have a three-wire, 125- to 250-volt system. If a motor connected to it can develop 50 horse-power at the full voltage 250, it can develop 25 horse-power when operated on one side at 125 volts. This will require two balancers of 12½ horse-power each, since there are two machines to take care of the unbalanced current. In other words, the balancers should have 25 per cent of the capacity of the largest motor, rated at its highest voltage; and this, of course, means that the balancers may be relatively small machines.

Motors operated on this system have their fields excited from some one of the circuits, usually the one of highest voltage. The armatures are connected to either line voltage as desired, and resistances are introduced to prevent too sudden changes of current at the transition points; additional speed variations are provided by weakening the motor fields. All these connections are made upon controllers of the cylindrical type, of which Fig. 42 is a good example. It represents 20-horse-power and 40-horse-power Bullock controllers without their covers; the larger size gives 12 running speeds forward, and 9 reverse.

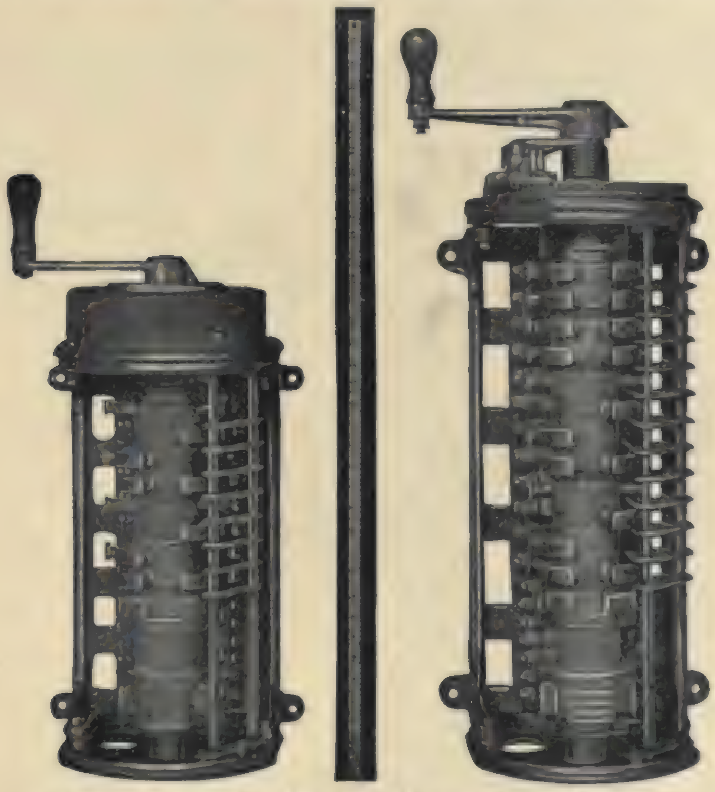


Fig. 42. Controllers Used with Bullock Multiple-Voltage System.
Allis-Chalmers Company, Milwaukee, Wis.

MECHANICAL POINTS OF MOTOR DESIGN

Motors need ample protection for the commutator and brush gear. This protection is well shown in the adjustable-speed motor illustrated in Fig. 43. This type of motor is also designed to run with the shaft vertical, in which case the lower bearing runs submerged in oil, and the upper bearing is made of anti-friction metal, running without attention. Motor end-frames or *bells* should be made so that they can be turned through 90° or 180°, to enable the machine to work with the oil wells in the proper position when mounted on a wall or ceiling. If the motor must work in a very dusty or dirty place, the ends may be protected with wire gauze covers, or even tightly enclosed with solid plates. In such cases, however, the machine has much more difficulty in dissipating heat; and for the same rise of temperature, the rating of an *enclosed* (and therefore unventilated) motor is not usually more than about half as much as if it were well ventilated. Fig. 44 shows one form of an enclosed motor. Sometimes the frames of enclosed motors are cast with projecting external ribs, to increase the cooling surface.

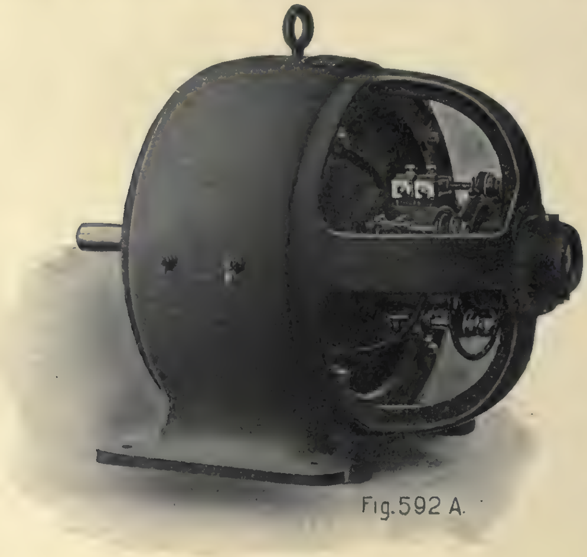


Fig. 43. Adjustable-Speed Motor.
Crocker-Wheeler Company, Ampere, N. J.

To obtain very low speeds without using a motor of disproportionately large size for its output, *back-gearing* is often used. Figs 45 and 46 give two views of a back-geared motor. To diminish wear and noise, such gears are often enclosed in cases and run in grease, like the gears of a railway motor.

Motors of large output—which, as a rule, are installed in more favorable surroundings and receive more careful handling than small motors driving individual machines—do not need special mechanical design. They are therefore built along the line of generators; and to a great extent the same parts are used for both.

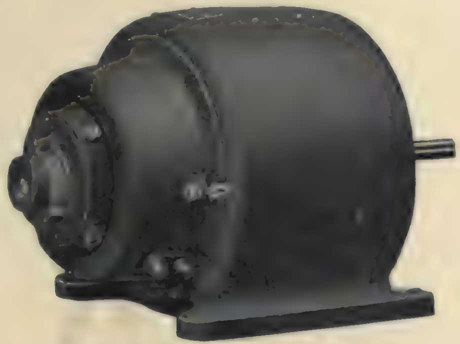


Fig. 44. Enclosed Type R Motor.
Westinghouse Electric & Manufacturing Company, Pittsburg, Pa.

ELECTRICAL POINTS OF MOTOR DESIGN

Since the motor is electrically identical with the dynamo, it is necessary merely to design a dynamo which will deliver the rated current at the given speed and the *counter-E.M.F.* of the motor. A single illustration will suffice. Suppose it is desired to design a 230-volt motor to deliver 10 horse-power at a speed of 825 revolutions per minute. The efficiency of such a machine should be about 85 per cent; so that the current required would be:

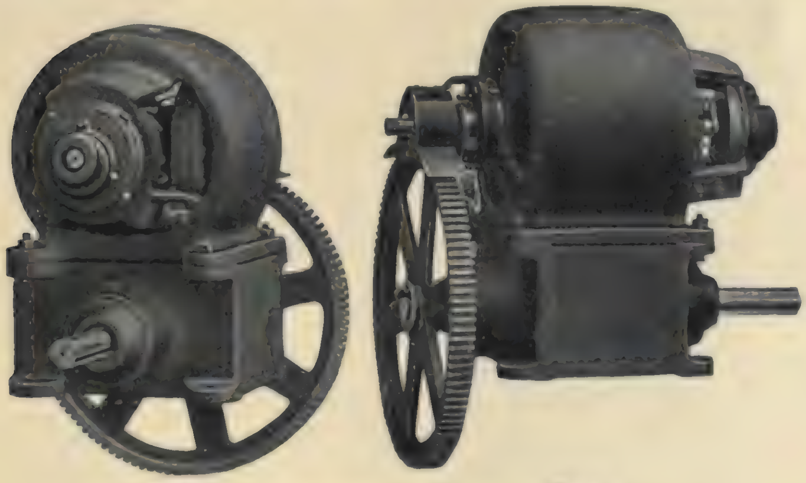


Fig. 45. Fig. 46.

Two Views of Type R Motor with Back-Gears.
Westinghouse Electric & Manufacturing Company, Pittsburg, Pa.

$$\frac{7{,}460}{0.85} \text{ watts} \div 230 \text{ volts} = 38.1 \text{ amperes.}$$

To allow for any error in estimating the assumed efficiency, let us say, in round numbers, that a current of 40 amperes would be required. The resistance of the armature of a machine of this size and voltage will be about 0.3 ohm. Then, from the fundamental motor equation, the counter-E.M.F. can be calculated:

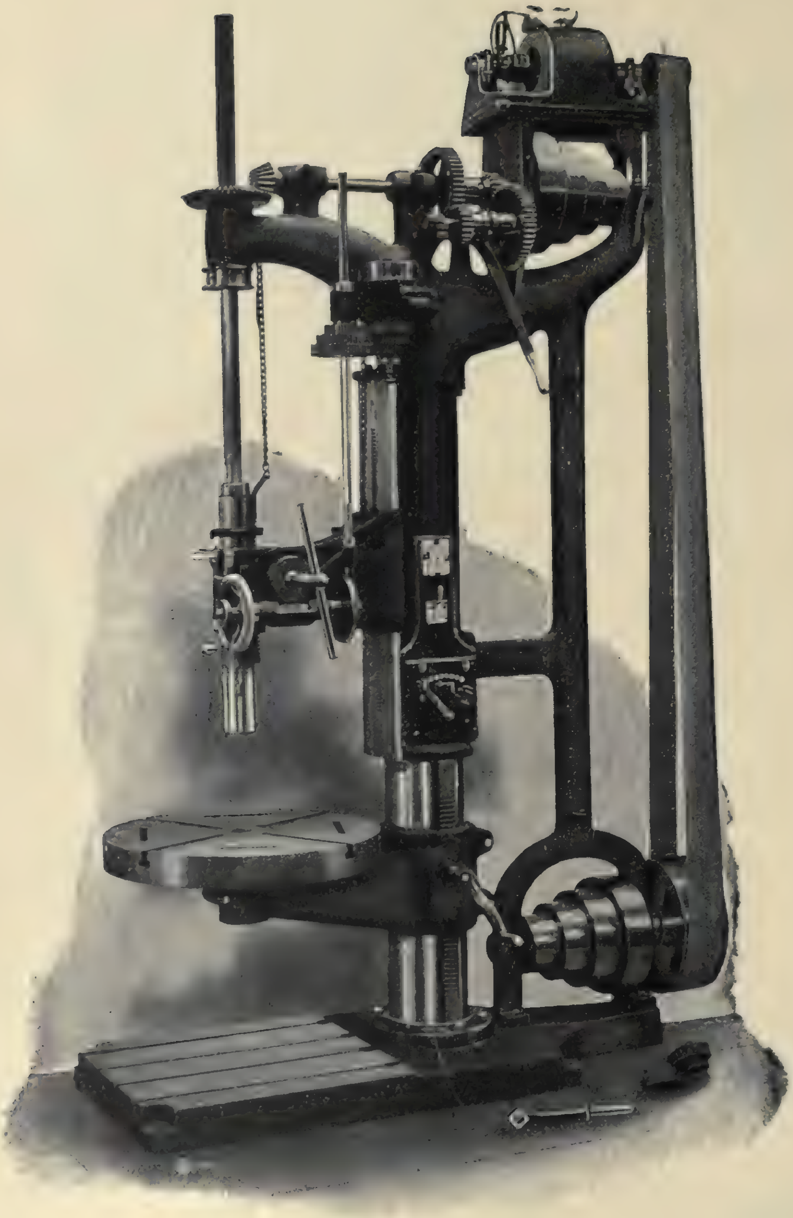
$$I = \frac{E - e}{R} = 40 = \frac{230 - e}{0.3};$$

whence,

$$e = 218 \text{ volts.}$$

That is, a dynamo should be designed whose output at 825 revolutions per minute will be 40 amperes at 218 volts, and whose armature resistance is 0.3 ohm. Its field windings should be calculated for excitation at 230 volts.

For supplementary reading on the subject of the Electric Motor, the reader is referred to the following works: *Dynamo-Electric Machinery*, by F. B. Crocker, and *Electric Railways*, by J. R. Cravath (published by the American School of Correspondence, Chicago, Ill.); *Electric Motors*, by Henry M. Hobart (published by Whittaker & Co., London and New York, 1904); and a series of articles entitled "Direct-Current Motors: Their Action and Control," by F. B. Crocker and M. Arendt, published in the *Electrical World* in 1907 and 1908.



MOTOR-DRIVEN DRILL.

The Hamilton Machine Tool Co.

ELECTRIC MOTORS IN MACHINE-SHOP SERVICE.*

I intend to consider the subject "electric motors in machine-shop service" from the standpoint of the shop engineer, whose one thought is economy in the broadest sense of the word. To such a man, the motor is but a single detail of the equipment—possibly one of the most important details, but only so when its relation to the problem as a whole, is understood. The development of alloy steels, permitting of cutting speeds from two to four times as great as was heretofore possible, requiring, in many instances, machines of new design; the introduction of the grinding machine, which is rapidly replacing the lathe for much finishing work; the milling machine; the electric motor as a means of driving; and types of management to assure efficient use of equipment, are among the most important factors requiring his attention.

The manufacturers of electrical apparatus too often defeat their own ends by overenthusiasm, or rather, by extravagant claims that they cannot possibly substantiate. There is no use trying to convince the shop engineer that the words "motive drive" are synonymous with "low cost," for he knows that efficiency attained depends upon the co-operation of a multitude of things, and primarily the intelligence with which the equipment is handled. If, however, the possibilities of the motor drive are properly presented, he can appreciate them better than any one else, for they fill a definite need, the importance of which he will understand.

It is not necessary to dwell upon substantial progress recently made in shop practice, which has resulted, in many instances, in greatly increased output with consequent reduction in cost. I shall consider rather what is needed to increase efficiency in the average shop, where it is still extremely low, for even when adequate funds are provided for the purchase of new equipment, the end in view is often defeated through lack of proper insight in connection with its purchases, installation, and use.

At the same time electrical manufacturers have not made the progress that would have been the case had they possessed a thorough understanding of shop requirements. Our experience has been confined largely to the installation and operation of electrical equipment under working conditions, therefore I shall treat the subject from this side, with the hope that I may bring more

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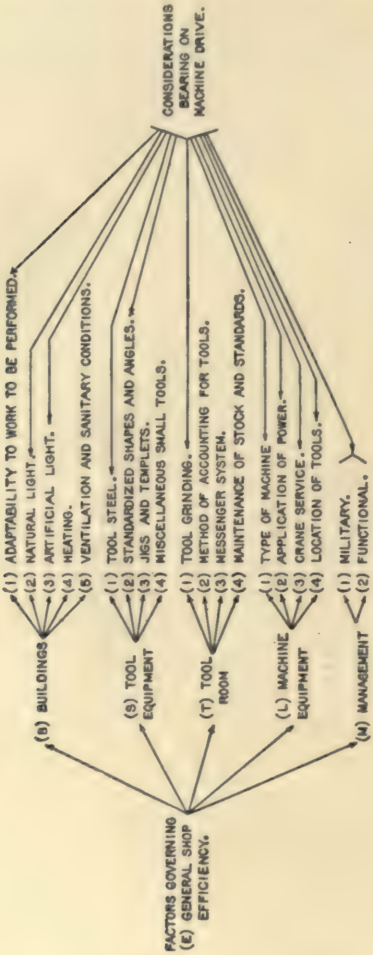
* This paper was presented before the International Electrical Congress of St. Louis, 1904, by Charles Day of the firm of Dodge & Day, Engineers, Philadelphia, Pa.; and is reprinted by special permission.

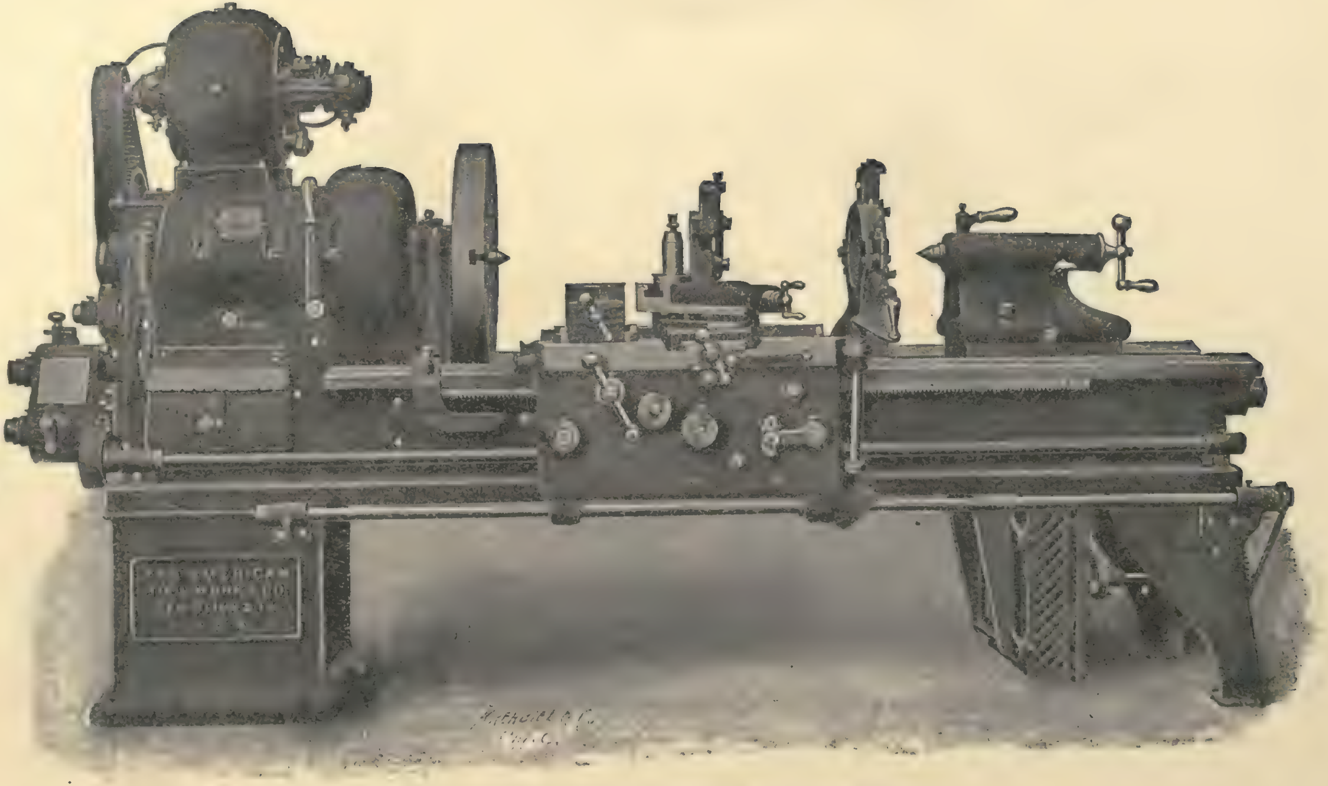

CONSIDERATIONS BEARING ON MACHINE DRIVE.
(1) ADAPTABILITY TO WORK TO BE PERFORMED.
(2) NATURAL LIGHT.
(3) ARTIFICIAL LIGHT.
(4) HEATING.
(5) VENTILATION AND SANITARY CONDITIONS.
(B) BUILDINGS
(1) TOOL STEEL.
(2) STANDARDIZED SHAPES AND ANGLES.
(3) JIGS AND TEMPLETS.
(4) MISCELLANEOUS SMALL TOOLS.
(S) TOOL EQUIPMENT
(1) TOOL GRINDING.
(2) METHOD OF ACCOUNTING FOR TOOLS.
(3) MESSENGER SYSTEM.
(4) MAINTENANCE OF STOCK AND STANDARDS.
(T) TOOL ROOM
(1) TYPE OF MACHINE
(2) APPLICATION OF POWER.
(3) CRANE SERVICE.
(4) LOCATION OF TOOLS.
(L) MACHINE EQUIPMENT
(1) MILITARY.
(2) FUNCTIONAL.
(M) MANAGEMENT
FACTORS GOVERNING (E) GENERAL SHOP EFFICIENCY.

Shop Considerations Bearing on Machine Drive.

Fig. 1.

clearly before the manufacturers the conditions they must meet and at the same time aid the customer in specifying his requirements and securing results.

Generally speaking, the electric motor (either for group driving or individual operation of machines) is conceded as the proper



MOTOR-DRIVEN AMERICAN ENGINE LATHE.

means of power distribution. My paper will deal with the subject under the following headings:

(1) Shop Requirements.
(2) Notes Concerning Motor-Drive Systems.
(3) Notes Concerning Different Makes of Apparatus.
(4) General Conclusions.

(1) SHOP REQUIREMENTS.[1]

My paper will only permit of a general outline of shop considerations bearing on the subject; these are illustrated in Fig. 1. Each factor must be carefully considered and, when treating the subject generally, certain assumptions made. For example, we are justified in assuming that the best tool steel should be used and design accordingly, while crane service and type of workmen are, on the other hand, matters depending on class of work handled and local conditions.

An intimate knowledge of shop practice is quite as necessary to the designer of electrical apparatus for machine *driving* as to the builder of the machine, and, while frequently difficult to show the direct bearing of the various features of management and methods upon a single factor, such as the one under consideration, the most useful conclusions can be drawn only by those familiar with the subject in detail. Improved systems of management are doing much to assure proper use of equipment, but in any event the need of explanation in connection with its operation should be eliminated to as great a degree as is possible. In other words, apparatus should primarily be designed to give satisfactory results in the hands of average workers. Where its adjustment and manipulation is dependent upon the operator, he must be fully considered in the design, but when attention is required for inspection at intervals only, the personal equation does not enter into the problem to as great an extent. Lathe and elevator drives illustrate the two cases.

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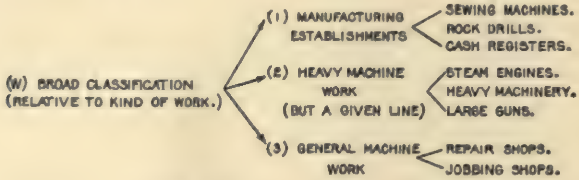
[1] The words "machine" and "tool," as used in connection with machine-shop work, are very frequently ambiguous. I will use them in the following sense: *Machine.*—Definition (Standard Dictionary). Any combination of inanimate mechanism for *utilizing* or *applying power*. A construction for mechanical production or modification. Example - Lathes, pneumatic drills, power shears, etc. *Machine Tool.*—This term is often confusing and need not be used in present paper. *Tool.*—Definition (Standard Dictionary). A *hand instrument*. Not a mechanism. Used directly for production. Examples.—Chisel, hammer, saw, etc.

Tools for removing metals will be further subdivided as follows: **Cutters, millers, drills, etc.**

If cuts are of long duration, the cutting speed can readily be determined by experiment, but this is not practical in the run of machine-shop work. The determination of cutting speed for miscellaneous work is a difficult matter, and must be given special study in each case, every means toward uniformity of product being resorted to.

The drive is but a detail of the machine. We should aim at a harmonious whole, not combining an efficient drive with an out-of-date tool. The motor-driven tool of the future should not be considered a combination, but a *unit* suited to certain specific ends. The motor-drive problem is essentially a matter for the machine builder to settle, and when a machine is purchased, the customer should have the assurance *that the drive has been given the same care in design and construction as any other part of the machine, and need not be considered as a distinct issue.*



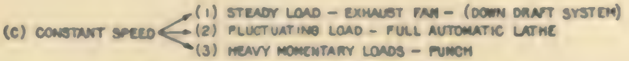
General Machine Shop Classification.

Fig. 2.

Machine shops may be broadly classified according to character of output as follows:

Shops of the first class can be laid out in every detail with regard to a definite need. Machines are purchased to do just one job, and frequently it pays to design special machinery for such duty. After it is properly adjusted for the character of material to be worked and for the cutters, no changes are required until better methods or facilities are developed. Here, as far as the drive is concerned, we find the simplest conditions. Usually constant speed with adequate power suits the case.

In shops classified under the second heading, little opportunity for duplication, in the sense just considered, exists. Machines must handle a variety of work, and even those purchased for specific operations are usually suited for other purposes so they may be kept busy the greater part of the time. Variation in size of work, material and cutters, demands an adjustable speed drive

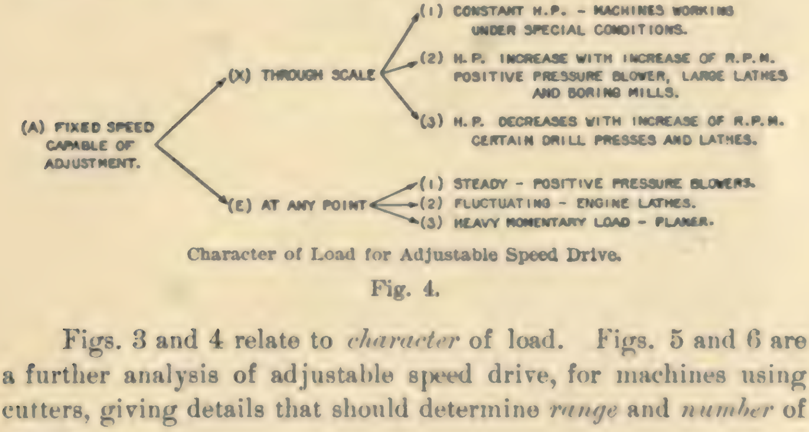

(C) CONSTANT SPEED
(1) STEADY LOAD – EXHAUST FAN – (DOWN DRAFT SYSTEM)
(2) FLUCTUATING LOAD – FULL AUTOMATIC LATHE
(3) HEAVY MOMENTARY LOADS – PUNCH

Character of Load for Constant Speed Drive.

Fig. 3.

together with change feeds, if most economical results are desired. This is true to a still greater degree for machines in the third class.

The drive requirements from a consideration of work to be performed can be further analyzed as shown below:


(A) FIXED SPEED CAPABLE OF ADJUSTMENT.
(X) THROUGH SCALE
(1) CONSTANT H.P. – MACHINES WORKING UNDER SPECIAL CONDITIONS.
(2) H.P. INCREASE WITH INCREASE OF R.P.M. POSITIVE PRESSURE BLOWER, LARGE LATHES AND BORING MILLS.
(3) H.P. DECREASES WITH INCREASE OF R.P.M. CERTAIN DRILL PRESSES AND LATHES.
(E) AT ANY POINT
(1) STEADY – POSITIVE PRESSURE BLOWERS.
(2) FLUCTUATING – ENGINE LATHES.
(3) HEAVY MOMENTARY LOAD – PLANER.

Character of Load for Adjustable Speed Drive.

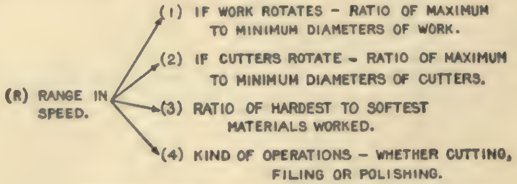
Fig. 4.

Figs. 3 and 4 relate to *character* of load. Figs. 5 and 6 are a further analysis of adjustable speed drive, for machines using cutters, giving details that should determine *range* and *number* of speeds.

Adjustable speed[2] may be desirable on grinding machines also, and in this case will depend on ratio of maximum to minimum wheel diameters and other matters that must be considered separately in individual cases.

[2] The words "variable speed" are now generally used for describing motors adapted for individual operation of machines, but to distinguish from the crane motor, for example, which is truly the variable-speed type, I shall use the words "adjustable speed" as describing a fixed speed capable of adjustment over a given range. Variable-speed motors are used principally for railway and crane service where the load is intermittent and torque variable. Direct-current apparatus has been developed to give such thoroughly satisfactory results for this duty that I shall not consider it other than in its relation to the general machine-shop problem.

Machines for punching and shearing, while usually arranged for constant speed, frequently require an adjustable-speed drive. For example, assume a punch operating at 28 strokes per minute. The operator may have work of such a character that he can easily punch a hole each stroke, while in another case, due to heavier sheets or greater accuracy required, he is compelled to skip every other stroke, punching but 14 holes a minute, while if the machine would permit he could readily do 28. Such a saving on this class of machinery usually yields a large actual return as the time required for setting up or making ready is, as a rule, small.

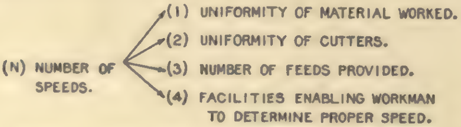

(R) RANGE IN SPEED.
(1) IF WORK ROTATES – RATIO OF MAXIMUM TO MINIMUM DIAMETERS OF WORK.
(2) IF CUTTERS ROTATE – RATIO OF MAXIMUM TO MINIMUM DIAMETERS OF CUTTERS.
(3) RATIO OF HARDEST TO SOFTEST MATERIALS WORKED.
(4) KIND OF OPERATIONS – WHETHER CUTTING, FILING OR POLISHING.

Factors That Influence Range of Speed.

Fig. 5.

The *amount* of horse-power required for machines of different types depends on the factors given in Fig. 7.

I have given the principal items to consider when designing or selecting machine drives, but to more fully explain the line of reasoning that should be followed, I shall assume definite conditions, and consider the equipment needed to fulfill them.


(N) NUMBER OF SPEEDS.
(1) UNIFORMITY OF MATERIAL WORKED.
(2) UNIFORMITY OF CUTTERS.
(3) NUMBER OF FEEDS PROVIDED.
(4) FACILITIES ENABLING WORKMAN TO DETERMINE PROPER SPEED.

Factors That Influence Number of Speeds.

Fig. 6.

EXAMPLE.

LATHE........ for general work in shop of A. ————. B. ————. Company, manufacturer of air compressors.

General features of this plant and its organization that influence type of drive (see Fig. 1).

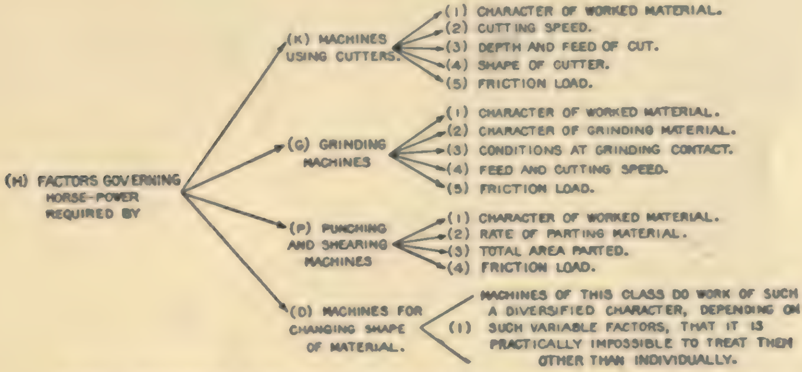
E.B.—1. The machine under consideration is to run in an old plant, hence no saving in cost of buildings could be effected by type of drive.

E. B.—2. The natural light at point where lathe is to be located is very poor, and it is important not to obstruct it any more than absolutely necessary.

E. B.—3. Artificial light has in the past been supplied by independent company, but they desire to install a power plant that will take care of this feature as well as power. It is desirable to depend largely upon general illumination by arc lamps with incandescent lights for detail work.

E. S.—1-2, and E. T.—1. For roughing work the best alloy steels, forged, treated, and maintained by special department, assuring uniformity and high efficiency, will be used.

E. L.—1, 2, 3, 4. Character of work necessitates constant use of power crane, making overhead belting and fixtures objectionable and difficult to provide for on account of location in main bay of shop. As cost of power in this plant amounts to less than 3 per cent of total cost of product, it is not a determining factor in character of drive.


(H) FACTORS GOVERNING HORSE-POWER REQUIRED BY
(K) MACHINES USING CUTTERS.
(1) CHARACTER OF WORKED MATERIAL.
(2) CUTTING SPEED.
(3) DEPTH AND FEED OF CUT.
(4) SHAPE OF CUTTER.
(5) FRICTION LOAD.
(G) GRINDING MACHINES
(1) CHARACTER OF WORKED MATERIAL.
(2) CHARACTER OF GRINDING MATERIAL.
(3) CONDITIONS AT GRINDING CONTACT.
(4) FEED AND CUTTING SPEED.
(5) FRICTION LOAD.
(P) PUNCHING AND SHEARING MACHINES
(1) CHARACTER OF WORKED MATERIAL.
(2) RATE OF PARTING MATERIAL.
(3) TOTAL AREA PARTED.
(4) FRICTION LOAD.
(D) MACHINES FOR CHANGING SHAPE OF MATERIAL.
(1) MACHINES OF THIS CLASS DO WORK OF SUCH A DIVERSIFIED CHARACTER, DEPENDING ON SUCH VARIABLE FACTORS, THAT IT IS PRACTICALLY IMPOSSIBLE TO TREAT THEM OTHER THAN INDIVIDUALLY.

Factors Governing Horse-Power Required for Different Types of Machines.

Fig. 7.

E. M.—2. The type of management being introduced at this plant should ultimately assure intelligent direction of work and proper use of equipment.

Referring to Fig. 2:

We find that this shop will come under the class indicated by the symbol *W-2.*

Referring to Fig. 4:

(A)—X—1-F-2. Majority of work (probably 80 per cent) will be steel and gray iron castings between 18 ins. and 48 ins. diameter. Maximum conditions call for removal of same amount of metal between these limits, and approximately constant cutting speed. Maximum horsepower requirements are consequently constant through the range, but subject to fluctuations at any one point below the said maximum.

Referring to Fig. 5:

R—1. At times it will be necessary to machine work as small as 10 ins. diameter, or as large as 60 ins. diameter; consequently a range in speed of 5 : 1 would be required for this purpose.

R—2. Cutters will always be stationary.

R—3. The ratio of hardest to softest material required by specification will be approximately 2 : 1. This will increase the necessary speed range to 10 : 1.

R—4. The majority of work will be roughing and finishing with cutters. Some filing and finishing with emery cloth will, however, be necessary, and for this purpose experience would dictate a cutting speed of 150 ft. per minute on 10 ins. diameter It will be necessary to provide a cutting speed of 15 ft. per minute on the largest diameter on account of the frail character and difficulty of driving some of the castings to be machined. Total range of speed is determined by limiting conditions of a cutting speed of 15 ft. per minute on 60-in. work and 150 ft. per minute on 10-in. work. I have purposely chosen these extreme conditions to better illustrate my point. In practice a 60-in. lathe is seldom required to run at 57 r.p.m.

$$\frac{150}{\frac{10 \times 3.14}{12}} = 57.3 \quad \text{r.p.m.}$$

$$\frac{15}{\frac{60 \times 3.14}{12}} = \quad .95 \text{ r.p.m.}$$

Consequently, for all practical purposes, the face plate of the lathe should run from one revolution per minute to 57 revolutions per minute.

Referring to Fig. 6:

N—1. It was stated above that the character of material would vary in the proportion of 2 : 1, this being a requirement of the products manufactured. Uniformity of material, or how nearly the requirements can be attained under shop conditions, is one of the factors influencing the number of face-plate speeds.

A fully-equipped laboratory, under the direction of an able chemist, who has entire charge of the cupolas and Bessemer steel converters, assures a much more uniform product in the plant in question than is usually the case. A great deal of experiment and investigation will be necessary however, before we can make definite assertions in this direction, but castings from the same pattern should not vary more than 20 per cent.

N—2. Cutter of the character indicated above (E.S.—1) should not vary in efficiency more than 10 per cent.

N—3. The full consideration of this point involves an understanding of the laws governing speed, feed, and cut for various materials. It will not be practical to include here full data on this detail. Hundreds of tons of steel and cast iron have been cut up to determine these relations, and constant experiment is necessary to keep abreast of rapid improvements. I will only say that it is quite as necessary to provide an adequate number of feeds as it is spindle-speeds, and in fact a limited number of either one of these factors will give efficient results provided a very close regulation can be had on the other.

In the present instance it was not considered advisable to specify changes to the standard feeding mechanism, as this feature had been well taken care of by the builder.

N—4. As the operation of the machine is ultimately governed by the facilities at the disposal of the machinist who runs it, it is absolutely essential that this point be given most careful study. It involves practically every feature of shop system and management, and it is only under such systems as that developed by Mr. Fred W. Taylor, of which functional foremanship is but a single detail, that the conditions, as outlined above, can be fulfilled. It necessitates that the operator of the machine be informed as to the character of the material, efficiency of the cutter, proper cutting speed in consideration of duration of cut, and many other equally important factors.

So it will be seen that we cannot arrive at any data which would enable us to specify definitely the number of spindle-speeds required. Our conclusions must necessarily be based principally on experience in shop practice, and for this reason engineers differ widely in their views. For the example under consideration, speeds increasing in increments of 15 per cent are, in our estimation, quite as close as can be used to advantage. It is well, however, to err on the safe side, providing too many speeds rather than too few.

Referring to Fig. 7:

H. K.—1, 2, 3, 4. Maximum permissible cutting speed on steel castings will be 60 ft. per minute; on gray-iron castings 60 ft. per minute (determined by actual requirements on a large variety of work). Maximum cut, cast-steel, $\frac{3}{8}$ in. deep, $\frac{1}{16}$ in. feed; gray-iron, $\frac{3}{8}$ in. deep, $\frac{1}{16}$ in. feed. (These conditions are established by character of work.)

The experiments conducted to determine the laws governing speed, feed, and depth of cut, for various materials referred to above (*N—3*) have been made available for purposes of design by means of slide rules, based on the derived empirical formulæ.

For the depth of cut and feed under consideration (cast-steel), the calculated pressure on the tool would be: 5,550, or horse-power required = $\frac{5550 \times 60}{33{,}000} = 10.1$ hp.

H. K.—5. The friction load can only be arrived at through experience and depends not only on the machine, but character and method of driving work. Experimental data on machines quite similar to the one under consideration would indicate 3 horse-power through the entire range as sufficient to allow for this purpose.

These conditions are plotted in Fig. 8. It will be noticed that the horse-power falls off on either side of the working part of the scale.

While it is easy to theorize as to the horse-power required for work of various diameters, in actual practice the conditions are about as I have shown. It must be borne in mind that the machine under consideration should be primarily adapted for the majority of work that it will handle. We have assumed that 80 per cent of this will be between 18 ins. and 48 ins. in diameter, so that work outside of these limits is the exception. On small work, such as would be handled, there is not likely to be opportunity for as heavy roughing cuts, and castings over 48 ins. in diameter cannot be swung over the carriage, nor would it be good policy to aim at high efficiency at this point for the additional cost would not be justified by the saving effected on such a small fraction of the total output.

As the horse-power between the working limits shown above was figured for the maximum cutting speed of 60 ft. per minute, we can plot a relation between revolutions per minute and horse-power. (See Fig. 9.) The selection of electrical equipment for this lathe will be taken up further on.

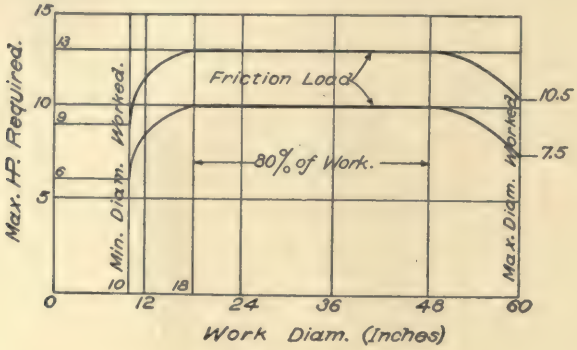


Fig. 8.

The analysis of conditions presented above is, as was stated, essentially a problem for the machine builder to work out—in other words, the electrical companies should look to him for general specifications covering motors and controllers.

When equipping machines of old design with motor drive, or remodeling them to better their efficiency, each one should be considered separately with regard to the special line of work it handles. As manufacturing becomes more specialized it will be possible for the builder of machines to design with more intelligence, for he can then treat a type as we have treated an individual.

To avoid repetition, I will assume the following conclusions have been established.

(1) Machines of present design of comparatively small work, requiring constant-speed drive should, in most instances, be grouped

and operated from motor-driven line shafts. Specifications for new machines for such duty should be made with a view to special requirements. Indirect savings in one plant may much more than offset additional cost of constant-speed motor on each machine, while this would not be true in another.

(2) For group driving, both direct- and alternating-current motors give thoroughly satisfactory results. In either instance, if properly installed, repairs should not be an important feature. In certain industries—the textile mills for example—the induction motor has decided advantages on account of close-speed regulation with varying loads and lessened fire risk, but for machine shops these features are unimportant.

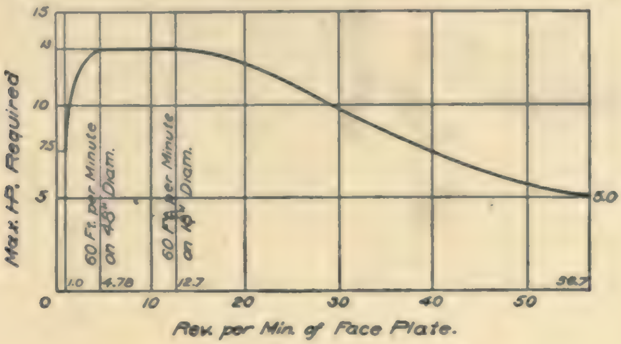


Fig. 9.

(3) Mechanical means of speed control, including step cone pulley and variable-speed countershafts, while suited for certain specific cases, do not meet the general requirements of machine drive. An attempt to obtain the necessary speeds by gearing, for example, is not only costly (if a sufficient number of changes are provided), but inefficient, in that as a rule, the machinery must be stopped to change from one speed to another, and cannot be controlled from an independent point.

(4) For adjustable speed work, direct-current motors only give satisfactory results at the present time. It is not practical by this means to use a range greater than 6 to 1, while in the majority of cases 3 to 1 gives the most economical results. In other words, in most instances, it is necessary to resort to a combination of mechanical and electrical control, the disadvantages of

each being largely eliminated by this means. For example, even where machines are handling a very general line of work, the greater part of it will be covered by a range of 3 to 1, so that if this amount is obtained electrically, gear changes will be seldom necessary, and at the same time a comparatively inexpensive motor required. Consequently the lathe requirements specified above are of quite as much value to the man who designs the mechanical features of the machine as the one who furnishes the electrical apparatus.

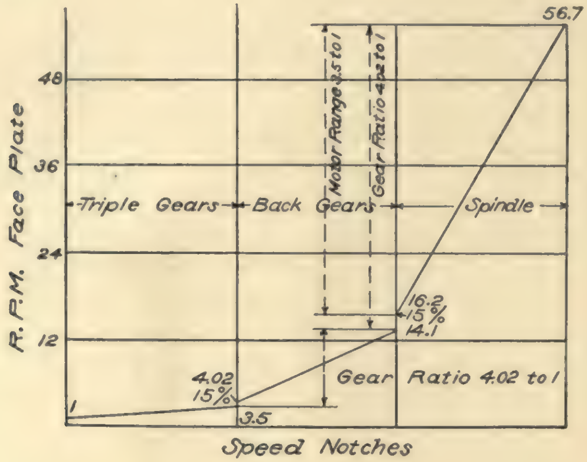


Fig. 10.

(5) Long transmission lines may make alternating-current desirable, and, for certain extended plants, the best results can be obtained by its use, together with motor-generator for direct-current variable-speed motors. If, however, but one kind of current will be available, decision should be largely governed by number of individual drives required. In many instances, while group drives may be desirable at the start, new equipment should be purchased with individual motors for the sake of adjustable speed and ease of control.

Returning to the 60-in. lathe considered above, the total speed range of 57 to 1 can be covered by the usual triple gear arrangement, with the resulting ratios shown on the chart. The range in motor speed, of 3.5 to 1, is quite practical and can be taken care of by any one of the systems referred to above.

I shall not dwell upon the strictly mechanical details of the drive, rather assuming that this part of the work is properly taken care of, but pass on to a consideration of the motor-drive systems.

(2) NOTES ON MOTOR-DRIVE SYSTEMS.

Systems now on the market for obtaining adjustable speed by means of motor drive, and advocated by prominent manufacturers, are given below:

(1) Field weakening only

(2) Double commutator motor combined with field weakening.

(3) Edison three-wire system combined with field weakening.

(4) Unbalanced three-wire system combined with field weakening.

(5) Four-wire multiple-voltage system combined with field weakening.

There are two classes of purchasers, with widely differing requirements, and to whom different systems appeal:

(1) The customer who buys motors for his own use to equip machines already in operation, or special machinery which must be given individual consideration.

(2) The customer who buys for an unknown third party. The builder of machines, for example, who manufactures his product without any knowledge as to whom the purchaser may be, and consequently must design equipments that will meet conditions existing in plants where his product is solicited.

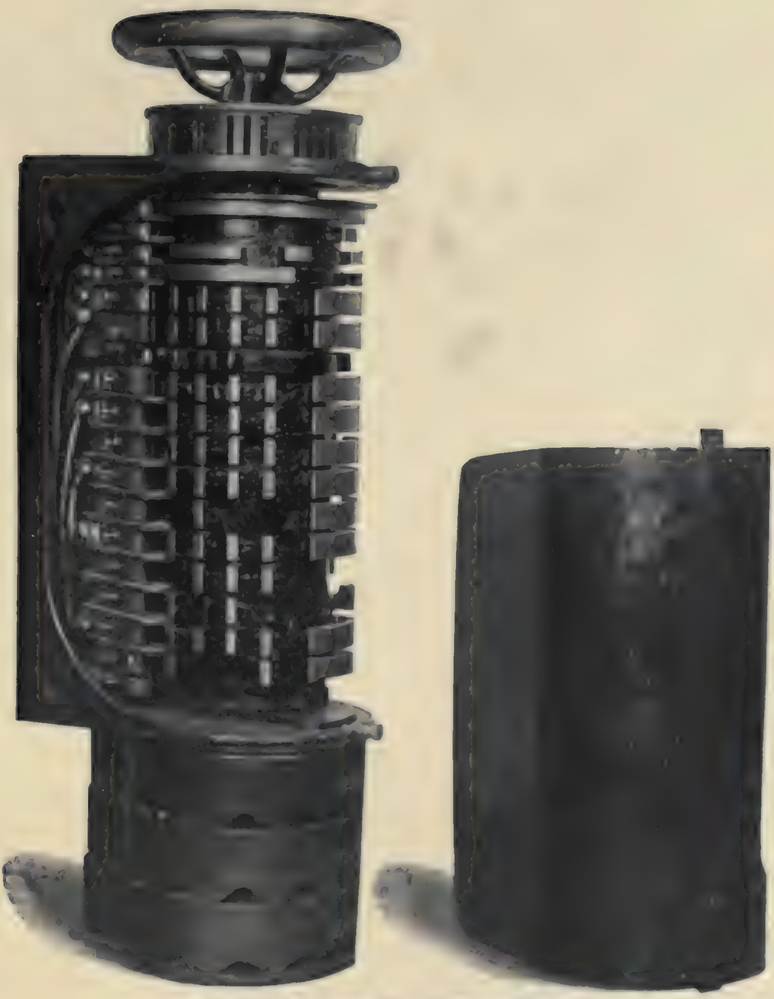
The electrical manufacturers have been slow in realizing this almost self-evident classification. The very essence of modern manufacturing consists in specialization, as it is only in this way that cost can be reduced to a minimum. Such establishments must be classified under the second division referred to above, and the product considered as a *type*, while in the first class given machines or given establishments can be treated separately.

Conditions in the past have in either case demanded a separate consideration of drive for practically every customer, on account of special character and numerous types of motor-drive equipment, but substantial progress, as far as the machine builders are concerned, will not be made until their product is manufactured complete in every essential. This means the adoption of a motor that can be operated on 110 or 220 volts, direct current, as one of these is not only found in nearly every large establishment, where it is used for cranes and lighting, but in many of the small shops.

The three- and four-wire systems, on the other hand, have been installed by a very small percentage of the shops who are, from time to time, purchasing new equipments, hence for commercial reasons such apparatus does not appeal to machine builders. It may, however, possess distinct advantages to purchasers of the first class who contemplate the motor equipment of an entire shop, either at once or as conditions demand. As they can exercise the greatest freedom in selection of equipment for motor drive, I shall consider the systems enumerated above from their standpoint. It will then be a comparatively simple matter to apply these conclusions to the more special conditions which must be met by the machine builders.

All customers, unless they employ consulting engineers, are called upon to decide themselves upon the system to adopt, and, as their experience does not, as a rule, cover the details of electrical engineering, they must depend largely on the statements put forward by electrical companies.

There is no doubt that the manufacturers in many instances have taken advantage of the special character of machine work to rate their motors in a way that is very deceptive. The words "full load" are almost universally abused, and as there is no standard specification adhered to, the only safe basis for comparison is through a knowledge of the weight and maximum speed for a given horse-power through a given range, with the understanding that a specified overload must be carried at any point for a certain time. Such an analysis would, according to the views of the various builders, give at least an intelligent idea of the equipment required to fill a definite need, but in a number of instances our experience has indicated that claims made by leading manufacturers have not been fulfilled in actual test. Machine-tool duty unquestionably permits of a different basis of rating from constant horse-power work in much the same way that street railway motors are rated on a basis of their own, but when one manufacturer adheres strictly to a rating of present standard, and another departs from it without the knowledge of the customer, the latter is likely



MULTIPLE-VOLTAGE CONTROLLER.

Crocker-Wheeler Company.

to be comparing bids on two radically different equipments. This we have repeatedly found to be the case. We feel that this matter should be given careful consideration by such a body as the American Institute of Electrical Engineers and a definite understanding arrived at.

I shall assume general familiarity with the systems under consideration. In general, a motor for a given maximum speed and a given range, to deliver a given horse-power through this range, will be at least as large when operated by field weakening only, as when a combination of either two or more voltages with field weakening is adopted. Unless the motor is specially designed for field weakening, it will be larger than in the latter case. We have been unable to obtain any satisfactory data from the engineering departments of electrical manufacturers concerning variation of horse-power with field strength, so prefer to base our conclusions upon tests which we have conducted in connection with work for various clients.

As the cost of variable-speed motors and auxiliary power transmission equipment, such as chain or gears, is in proportion to the speed at which it operates, we should see that the latter is as high as is consistent with the various engineering considerations. A number of the manufacturers of motors do not give sufficient thought to the adaptation of motor speeds to available means of transmitting power to the machine. There are three methods in common use, namely: leather belts, gears (including worm and spiral gearing) and chain. While the great flexibility of the belt, in relieving the machine of sudden jar, has distinct advantages in certain instances, gears and chain are used in the majority of cases for individual drive.

(1) FIELD WEAKENING (WITH A SINGLE VOLTAGE).

A number of manufacturers have recently placed on the market motors designed to run on a single voltage, but that may be varied in speed by means of field weakening over a range, in some cases, as high as 6 to 1. Until recently, ranges as great as the above have not been considered practicable and our tests of motors of various makes have indicated that in this respect much can be accomplished through careful motor design. Manufacturers that adhere to the simple shunt type do not advocate, except for special work, a range exceeding 4 to 1, while others who have adopted either additional poles or special windings claim to have eliminated the difficulties usually encountered, and are prepared to furnish motors giving any variation desired. These types, however, have not been in operation a sufficient length of time to enable us to confirm their statements.

We have found that customers are frequently misled concerning the size of frame required for a given duty for motors operating on this system. As the horse-power that can be developed with a given frame is in proportion to the speed of the armature, it is necessary to use, for a range of 4 to 1, a motor frame rated at least four times as large as the power required if practical speeds are not to be exceeded. Even such a frame will not, in most cases, make it possible to rate the motor as liberally as is the case with standard constant-speed apparatus, as the exceptionally strong field required is likely to cause heating at the slow speed, and at the high speed the weakened field will cause poor commutation.

We have not yet experimented with a motor of this type that would operate continuously under the full-load current at its highest speed without giving some trouble at the commutator. It is true, as was stated above, that such conditions would rarely be met in the machine shop, but to purchase with intelligence it is necessary to know how much manufacturers depend on this fact. Motors with a range of 3 to 1 have already been successfully applied to machines requiring a comparatively small amount of power, although, as will be pointed out later, the apparatus has not been perfected as fully as is the case with other systems.

If the lathe considered above be equipped with apparatus operating on this system, the relation between motor horse-power and that required by the machine, shown in Fig. 11, should fulfill the conditions satisfactorily, as the upper curve is drawn through maximum values, and when they are reached the overload on the motor would only be 30 per cent.

Referring to the dimensions and ratings furnished by one of the manufacturers, whose apparatus has shown up very favorably under test, we find that a motor weighing 1,615 lbs. will deliver 10 horse-power between a range of 350 r.p.m. and 1,050 r.p.m., or one weighing 2,300 lbs. will deliver 10 horse-power between 225 r.p.m. and 900 r.p.m. We recommend the use of the last frame, as satisfactory commutation should be assured by the smaller speed range, namely, 225 r.p.m. to 787 r.p.m.

(2) DOUBLE COMMUTATOR MOTOR (COMBINED WITH FIELD WEAKENING).

The additional cost of the double commutator motor, together with the maintenance of two commutators instead of one, are objections to this system that, in our estimation, offset its advantages for other than special cases.

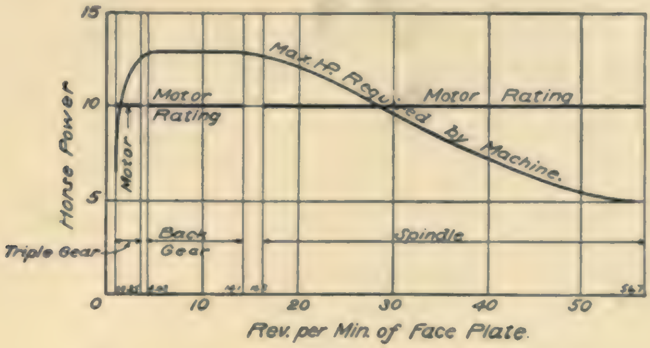


Fig. 11.

(3) EDISON THREE-WIRE SYSTEM.

The combination of the Edison three-wire system with field weakening permits of a range of 4 to 1, with but 100 per cent increase in speed by the latter means, and, consequently, eliminates commutator troubles to a marked extent.

The balanced three-wire system has been adopted quite generally in the past for lighting purposes, and may be obtained either by means of standard generator, together with a separate balancer, or by providing the former with slip rings connected to an autotransformer from the middle point of which the neutral is taken. The latter arrangement is advocated by manufacturers of this apparatus.

The selection of motor to operate on three-wire system for the 60-in. lathe should be based on curves shown in Fig. 12. The same assumptions are made regarding overload as in the former case.

The motor required for these conditions, according to one of the principal advocates of the Edison three-wire system, would weigh 2,600 lbs. and operate from 220 r.p.m. to 880 r.p.m.

(4) THE UNBALANCED THREE-WIRE SYSTEM.

The unbalanced three-wire system was developed to give, with a minimum size motor, a range somewhat greater than 6 to 1.

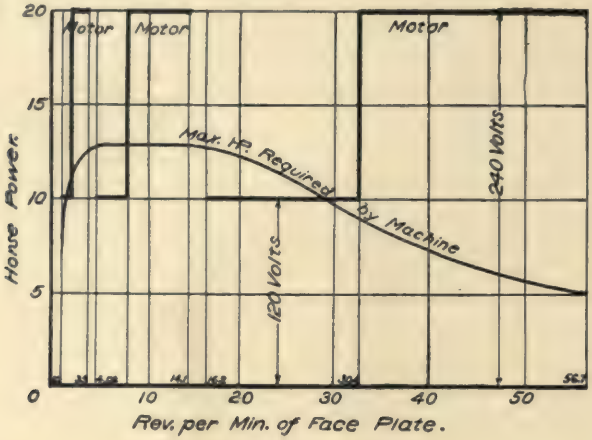


Fig. 12.

For a range of 4 to 1, or under, it has no advantage over the balanced three-wire system, nor does it possess the several good features of the one last named.

(5) FOUR-WIRE MULTIPLE VOLTAGE SYSTEMS.

The principal advantage of the multiple-voltage system is that absolutely standard motors (the same as are used for constant-speed duty) are used with perfectly satisfactory results. This is not true of any of the other systems. Motors designed to operate on a three-wire system must run with full field, full voltage at about half the speed of a constant-speed motor for the same duty, therefore cannot be economically used for the latter purpose. This is true to a still greater degree for motors designed to give a wide range of speed by means of field weakening only.

The maximum range in speed obtainable by the system under consideration depends upon the voltages adopted and the amount the field is weakened, but for purposes of economy, except where constant torque is required, the working scale is usually confined to the higher voltages. The lower voltages, while used chiefly for starting, prove of great assistance at times for setting up work.

The two systems which have been advocated differ in that one requires an arithmetical series of voltages, and the other a geometrical series. In either case a balancer, or specially designed generator, is required to give the voltage referred to and four wires employed for distribution. These two features are frequently cited as disadvantages that more than offset the good points of this system, but, in reality, they do not complicate matters to any great extent nor add materially to the cost of a large installation.

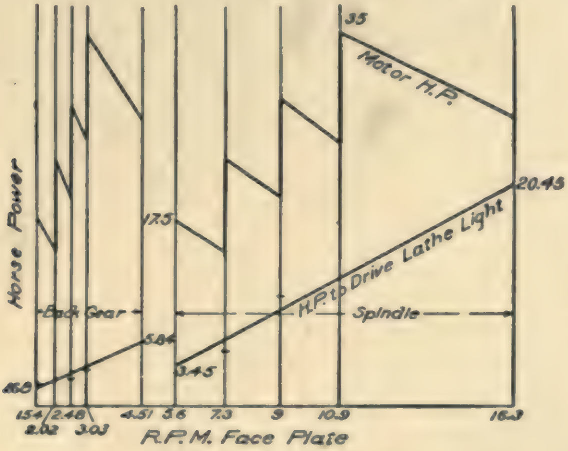


Fig. 13.

While, as stated above, the average machine tool may be considered as requiring constant horse-power through its working range, in numerous instances, particularly when dealing with large machinery, we find that requirements call for an increased horse-power with an increased speed. For such cases the multiple-voltage system is most desirable as is clearly shown by the curves in Fig. 13.

This data relates to a large gun lathe, driven by multiple-voltage apparatus. The lower curves are drawn through points determined by actual test and show the power required to drive the lathe with face plate in place, but otherwise running light. The power available for useful work is represented by the vertical height between the curves just referred to and the upper ones, which show the relation between horse-power and speed of a standard 35-horse power Crocker-Wheeler motor. Such examples are, of course, exceptional.

Thus far, I have assumed the use of the same range in motor speeds, when operating on the spindle, backgear, and triple gear, and in the case of field weakening motors, or those operating on a balanced three-wire system and rated as above there would not be any advantage in doing otherwise. The characteristics of the multiple-voltage system, however, are such that a smaller motor can frequently be used. The gear ratios are determined by the nature of the load curve. This fact was borne in mind when plotting the curves shown in Fig. 14 relative to multiple-voltage equipment for lathe A.–B. Company.

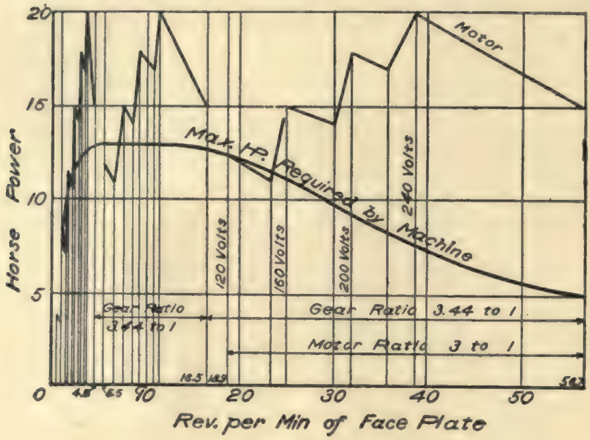


Fig. 14.

A motor weighing 2,350 lbs. and operating from 236 r.p.m. to 820 r.p.m. is recommended by one of the leading manufacturers of this apparatus. They prefer to rate their motors very conservatively, which accounts for the decrease in horse-power with field weakening. By actual test their motors stand up under these conditions as well as many other makes that are said to deliver constant horse-power through a range of 2 to 1.

(3) NOTES CONCERNING DIFFERENT MAKES OF APPARATUS.

In every instance final decision must rest with the perfection of apparatus. One of the most important details so far as efficient shop use of the motor drive is concerned is the controlling mechanism. For machine-shop duty thoroughly rugged and compact controllers are required. No contacts should be exposed as is now the case with the apparatus furnished by a number of manufacturers of field weakening motors. With thoroughly efficient apparatus it is practically impossible to damage either the motor or controller by the rapid operation of the latter. I do not mean by this that it is well to swing the controller handle suddenly from the off position to the full-speed point, but such action should not result in destructive sparking at the commutator or arcing at the controller points.

The satisfactory operation of a controller for the conditions under consideration depends largely upon the success with which the manufacturer has fulfilled the following conditions:

(1) Controllers should be completely inclosed in iron casing.

(2) It should be impossible through the manipulation of the controller to stop the motor at any place on the scale other than the off position.

(3) Rapid operation of the controller should not cause serious damage to either motor or controller.

(4) They should be so designed that they can be easily operated from a convenient point on machine.

(5) A sufficient number of speeds should be provided, depending on machine requirements.

(6) Controllers that require frequent operation must be designed with liberal contact surface and more rugged in every respect than those used principally as "speed setters," and as a result only operated at intervals.

(7) The design should permit of repairs with the greatest ease. In this connection the location and type of resistance grids should be given careful consideration.

(8) Each speed should be clearly defined either by a star-wheel and pawl or other means.

A number of manufacturers have placed on the market controllers that are giving good results, and in most respects comply with the above requirements.

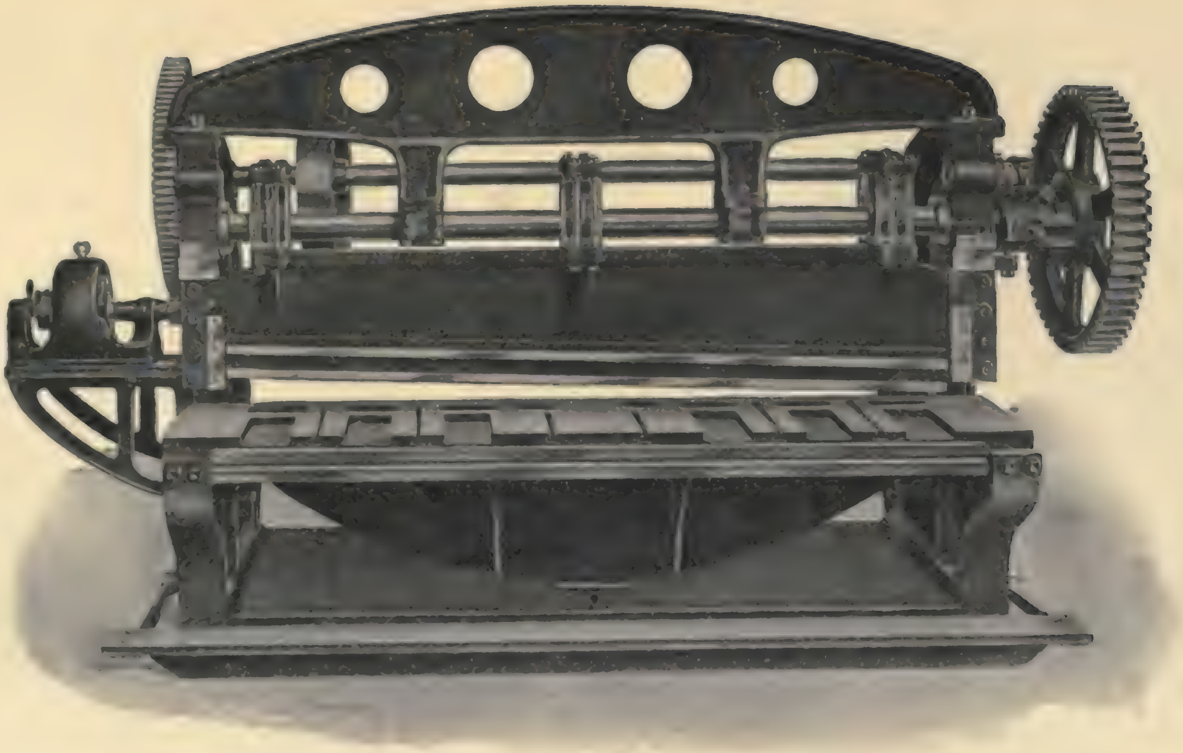
Motors have been designed to accompany these controllers that are well suited for application to machines, in so far as their external dimensions are concerned, but at the same time we feel sure that the electrical manufacturers who are willing in certain cases to depart from present designs will gain a strong position with the machine builders.

(4) CONCLUSIONS.

In all probability a paper such as I have prepared for this meeting of electrical engineers, would have seemed decidedly out of place some years ago. I have dealt with matters which would then have been considered the business of the machine builder or mechanical engineer, and not requiring the thought and study of the electrical profession. It is now realized, however, that the motor-drive problem presents many new features, and is a distinctly different one from the manufacture and sale of standard generators, for example. The earning power of the latter is largely dependent upon the design and workmanship, features that can be passed upon before the machinery leaves the works. If a power plant is found to be too small, more units can be readily added without in any way interfering with those in use. On the other hand the earning power of a motor equipment for individual operation of machines depends largely on conditions over which the manufacturer has no control. The continued growth of this department of his plant, however, is governed by results actually obtained with his product under working conditions, so to protect himself he is called upon to see that the proper equipment is selected, and if possible, advise as to its use. As far as the customer is concerned, it would usually be better for him to close his eyes and grasp any one of possibly four makes of apparatus, devoting his time to its proper installation and operation, rather than reversing the process as is so often done.

The conclusions reached above concerning the motors required for the 60-in. lathe are summarized in the table below:

	Weight.	Min. R.P.M.	Max. R.P.M.
Field weakening	2,300	225	787
Three-wire system	2,600	220	770
Four-wire system	2,350	235	820



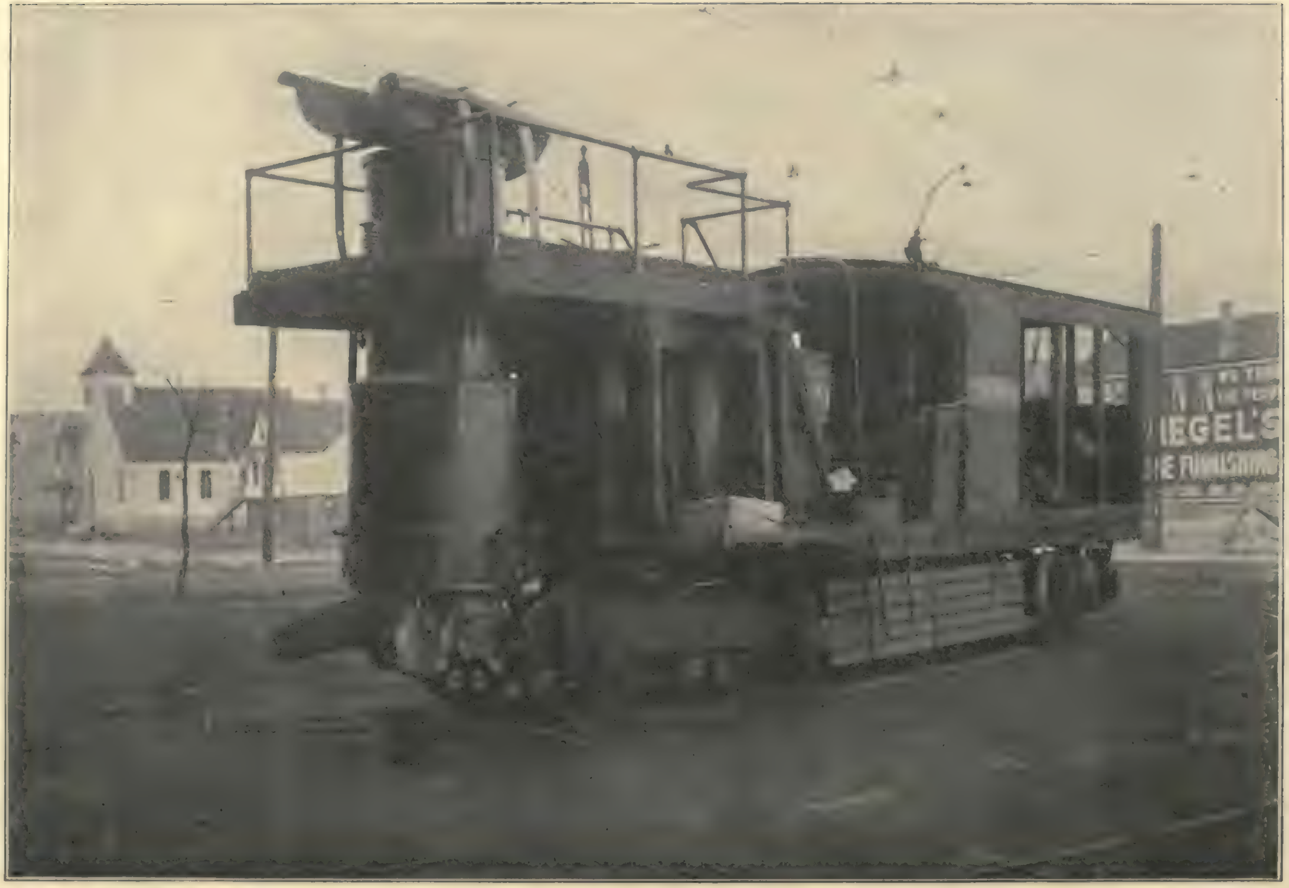
GUILLOTINE SHEARS. MOTOR DRIVEN.

Erie Foundry Company.

It must be remembered that the ability of these motors to fill the imposed conditions was not determined by actual test, the data being the recommendations of well-known electrical companies who manufacture the respective types of apparatus. These figures should at least make it clear that many statements constantly made concerning the size of motor required for a given horse-power and speed range cannot be other than erroneous.

I pointed out above the conditions which must be met by the machine builder necessitating the selection of a type that does not require for its operation special auxiliary apparatus. While motors operating on two wires and giving a range as high as 4 to 1 by means of field weakening do not at present give as good all-round results as those operating on the multiple-voltage and three-wire systems, we feel that their adoption by the manufacturers referred to is certainly justified. When this is more fully appreciated the electrical companies should rapidly achieve better results in this direction.

The customer purchasing for his own use should, on the other hand, *differentiate clearly between the machine builders' requirements and his own*, for in many cases he can secure more satisfactory results, all things considered, through the adoption of a system combining with field weakening a number of voltages.



PORTABLE CUPOLA FOR CAST-WELDING JOINTS OF STREET CAR RAILS.

ELECTRIC WELDING

METHODS OF WELDING

Ordinary Welding. Welding done by the ordinary method is one of the very skilful processes in the mechanic arts. It is generally performed by heating the pieces to be welded to a temperature at which they are in a more or less plastic condition, and then forcing them together either by direct pressure or by means of blows.

When the pieces are placed together, the temperature must be high enough to melt the scale, or oxide, with which nearly all heated metal is covered. This is necessary in order that the scale may be forced from between the welding surfaces, and a clean joint left. As a general rule, the pieces to be joined are heated in an open fire; and as there is always more or less air present, the oxygen in the air attacks the metal, forming an oxide on the heated surfaces. In order to make a perfect weld, there must be no foreign matter present between the surfaces to be joined, and the oxide formed in the fire must be gotten rid of in some way. With some metals—for example, tool steel—the welding temperature is below the melting temperature of the oxide; and in order to make a sound weld, it is necessary to add *flux* during the heating, to melt this oxide. This flux also aids in the welding by forming a protecting covering over the heating surfaces, shutting out the air, and to some extent reducing the oxidation.

Any metal which passes slowly from the solid to the molten state while being heated, welds easily. In other words, any metal which has a comparatively large range of temperature through which it remains in a semi-pasty condition is easily weldable, as this range of temperature allows an appreciable amount of time for the necessary hammering of the joint together, before the metal becomes too cold to stick properly. On the other hand, any metal which has a comparatively small range of temperature between the solid and molten states is difficult to weld, as the metal cannot be properly worked in the limited time allowed by the cooling. Brass is a metal

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of the latter sort, while wrought iron is perhaps the best example of the easily weldable metals.

Another difficulty experienced in ordinary welding is that the heat is applied directly only to the outside of the piece, and all which reaches the center must first penetrate the outer metal. This often results, where the heating has been too rapid, in the burning of the outside metal before the center is hot enough to weld.

One great drawback to ordinary welding is that the welding temperature is held by the pieces such a short time that the placing of the pieces together and other manipulating has to be done almost instantly.

All of the above difficulties are very much lessened, if not entirely done away with, in the electric process of welding. In the most common electrical method, the pieces may be placed in exactly the right position, and as much time taken as necessary. Then, when everything is adjusted, and the work clamped firmly in place, the heating and welding are done, the pieces being securely held in place during the entire process.

Electric Welding. All methods of electric welding or heating are based upon one elementary fact—that all substances offer resistance to the passage of an electrical current, and that when a current of electricity is passed through any material, this resistance causes the temperature to rise. The larger the amount of current flowing, the faster the rise in temperature. Consequently it is only necessary to pass a sufficiently large amount of current through a body of metal to heat it to almost any degree in a very short time.

Probably the most common illustration of this principle is found in the ordinary incandescent lamp, where the resistance of the carbon filament causes it to become almost white-hot when the current is passed through it.

If two pieces of metal forming the terminals of an electric current be brought in contact, the point of contact will naturally be the point of greatest resistance. If a current be passed through the pieces, the heating effect will be greatest at the joint; and as the temperature rises, the metal will offer still greater resistance to the current, causing a high local heat at the junction of the two pieces. This point is well shown in the arc lamp, where the resistance of the short air-gap causes an intensely high local heat.

METHODS OF ELECTRIC WELDING

There are three general methods of electric welding in use, briefly described as follows:

1. ARC METHOD. In what is known as the *arc method* of electric welding, the pieces to be welded form together one terminal, and a carbon point or pencil forms the other; or each piece may form a terminal, much after the manner of the arc lamp.

2. SUBMERSION METHOD. In the so-called *submersion method*, the work is heated by *submerging* in a heated bath, or in some moderately conducting liquid contained in a metal-lined tank.

The above two methods are what might be termed *high-voltage methods*, as distinguished from the following process, which is a *low-voltage* method.

3. THOMSON PROCESS. In the *Thomson* process, the heating is done by passing a current of very low voltage through the work while the pieces are in contact.

The first two methods are not so commonly used as the Thomson process, but have certain characteristics which peculiarly fit them for certain purposes.

ARC METHOD

In this process of welding, the pieces to be joined are placed together, and contact made with the positive pole of a continuous current, the negative being a carbon point held in suitable grip.

The carbon is brought in contact with the work, and an arc is drawn, the heat from which raises the joint to a welding or melting temperature. Sometimes plates are welded in this way, being first lightly riveted together to hold them in place.

This method is said to give excellent results for *local* heating, where a spot only is to be heated. Another application of the same principle is the filling of blow-holes in defective castings. A direct current is used, and the holes are filled by melting in metal with the heat of an arc drawn from the negative carbon to the casting, which is connected to the positive side of the circuit.

Sometimes, in place of using a carbon point for a negative electrode, a small bar of the metal which it is desired to melt into the hole is used. When the electrode is made of the metal itself, Houston and Kennelly give the following figures for the size of bar and current required: "The diameter of electrode is usually from 6 to 10 mm., and the current density about 8 amperes per square millimeter of active surface of the metal electrode." Reduced to English measurements, this makes the metal electrode about ¼ inch or ⅜ inch in diameter, and the current required about 5,160 amperes per square inch, or from about 225 to 600 amperes for the sizes of electrodes given.

It should be noted that in this method a comparatively high voltage is used (about 50 volts, or higher); and this to a large extent distinguishes this process from the Thomson method, which is a low-voltage operation.

One precaution must be taken in work of this character, and that is first to heat the casting to be operated on, to as near a red heat as possible, at least all around the part to be treated. This preliminary heating may be done in an ordinary forge fire, the electrical current being used only for melting in the filling. If this preliminary heating is neglected, the unequal contraction in cooling is very liable to cause the filling to loosen from the hole.

In using the arc it is of course necessary to have some variable resistance in the circuit to control the amount of current flowing. It should also be remembered that the positive terminal is always the hottest part of the arc, and for this reason the work itself should always be connected to this side of the circuit.

The arc principle is sometimes used for fusing wires together, where no very great strength is required but favorable conditions for electrical conduction are sought. The wires to be joined are made the terminals, and are brought together until an arc is formed. The current is maintained until the ends are heated to the welding or melting point, when it is shut off, and the ends of the wires pushed together. A direct current at about 50 volts may be used. On the end of the positive wire, a small ball of molten metal will form, and the end of the other wire may be pushed into this to make the joint.

Arc Method of Cutting Steel Beams and Piling. Perhaps the most valuable application of the arc method is its use in cutting—or rather, *melting in two*—of steel beams or other metal parts in wrecking a building, or in cutting holes in parts difficult of access.

The operation is much the same as that followed in filling blow-holes in castings; but in this case the heating is continued until the metal melts and runs, leaving a hole in the work. In this way holes have been cut, or burned, in steel vaults; and it is not at

ELECTRICALLY WELDED STREET-CAR TRACK

Light Patches on Rail in Foreground Indicate Where Sand Blast was Used. Rail is Ready to Weld. Rail in Background has Been Welded.

all uncommon to cut out parts of floor-beams in buildings, for stairways, etc., by the same method.

This makes a cheap as well as an effective method of doing the work, as the power used need not be over 25 or 30 horsepower. When central station power is available, it should be used; but when it is not convenient to obtain power from such a source, a self-contained generating set consisting of a gasoline engine and dynamo may be employed to advantage.

Work of this kind has been done in office buildings during the night, utilizing the power which during the daytime is used for running elevators, etc.

Either direct or alternating current may be used.

Messrs. Houston and Kennelly give the following data based on observations in connection with several pieces of actual work:

> On some work done in San Francisco, a 25-kilowatt continuous-current generator, direct-connected to a single-cylinder gasoline engine, was used. A 15-inch I-beam was cut in two in about 20 minutes. The current was about 250 amperes at from 90 to 100 volts.
>
> In New York City some work was done with central station alternating current. Four 20-kilowatt single-phase transformers connected in multiple were used with a secondary E. M. F. of 50 volts. In this case some steel piling was cut off, the depth of cut varying from ½ inch at the middle to 3½ inches at the ends. This piling was cut at the rate of about 10 feet per day of 8 hours, using about 256 kilowatt-hours, requiring about 650 amperes at 50 volts.
>
> Calculating current as selling at 10 cents per kilowatt-hour, the above method of cutting piling was found to save over $10.00 per day, in addition to the time gained.
>
> The carbon electrode was 1¼inches in diameter, and was clamped between copper plates each 5 inches square and ½ inch thick, to which one of the wires was fastened. The other wire was bolted to the piling. It was found necessary to replace the copper plates every 15 hours, as the intense heat would buckle the plates in that time.

When doing this sort of work, it is absolutely necessary that the operator be thoroughly protected with asbestos mask and gloves, and thick black glass goggles. Under no circumstances should the naked eye be exposed to the glare of the bare arc, for, while the effect may not be felt immediately, serious results are almost sure to follow even a comparatively short exposure.

Electric Crucible and Furnace. The electric crucible is one of the applications of the arc principle described above. A graphite or other crucible made of a heat-resisting material which is a good conductor of electricity is used as the positive pole, the negative being a stick of carbon. The arc is formed by turning on the current and placing the carbon in contact with the crucible, and then separating them far enough to draw an arc. The substance to be fused is placed in the crucible, and melted by the heat of the arc. The temperature of the arc is about 3,400° C.

A sketch of a simple arrangement of such a crucible is shown in Fig. 1. This principle is used to some extent in metallurgical work, where an extremely high heat is required; but it has not come into commercial use to any great extent, although there are several large furnaces made on much the same plan.

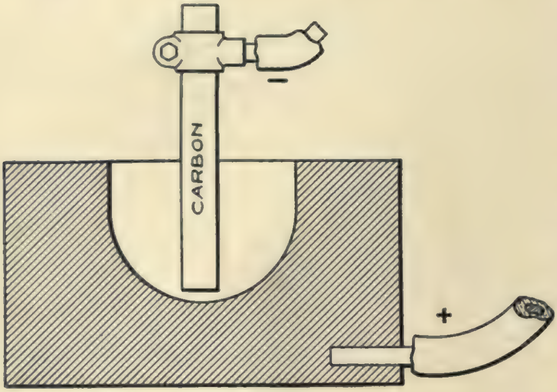


Fig. 1. Electric Crucible.

The same principle, with slight modifications, is used in one form of the electric furnace. In this furnace, two carbons are used, being placed horizontally over a shallow crucible in such a way as to form an arc between the two pieces. The heat is still further confined by means of a cover consisting of the same material as that of which the crucible is made, and having a slight hollow over the arc. The crucible and cover are generally made of lime. A sketch of such a furnace is shown in Fig. 2.

SUBMERSION METHOD

This method, like the arc method above described, is a high-voltage method; but the manner in which the work is handled is very different in the two methods. The submersion process is very limited in use, but spectacular in operation, and for this reason is sometimes used to draw crowds at exhibitions.

A metal-lined tank is used, which is filled with some liquid like brine, acidulated water, or other conducting fluid of similar character.

The lining of the tank is connected to the positive wire, the negative wire being connected to the metal to be heated. This may be done by having the negative wire soldered to a pair of tongs used to hold the work; or the work may be rested against a bar placed across, but insulated from, the tank, this bar being connected to the negative wire.

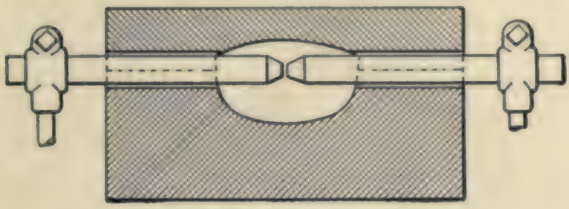


Fig. 2. Electric Furnace.

On arrangement for thi ssort of work is shown in Fig. 3. The heating is regulated by the amount of bar submerged in the liquid, the part below the surface being the part heated. The bar of metal to be heated is grasped in the tongs or rested on the "live" bar, and plunged into the solution in the tank. It begins to glow almost immediately, and soon becomes welding hot. The effect is very startling, particularly as the heated bar may at once be taken in another pair of tongs, and cooled in the same solution it was heated in. Or a switch may be arranged to cut off the current, the piece still held in the same tongs used for heating, plunged back into the bath, and immediately cooled.

By heating under water in this way, oxidation is prevented; but the heat is not very easily controlled. Consequently there is the same danger of overheating, and the same inadaptability to range of temperature, that there is in welding by the ordinary method. When welding is to be done by this method, the pieces must be scarfed in the usual way, heated separately, placed together after heating, and the weld completed by hammering together in the regular way. In fact, the only difference between this method of welding and the ordinary forge method lies in the fact that the heating

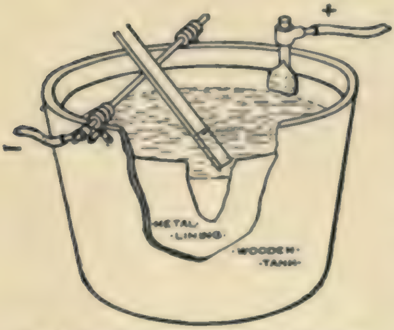


Fig. 3. Submersion Method of Welding.

in one case is done electrically, and in the other in the forge. Only such metals as can be welded at the forge can be handled by this process; and it would hardly be practicable to attempt to work with such materials as copper or tool steel.

Metals may be—and sometimes are—heated in this manner for drop forging, as it gives a very clean heat free from scale.

ELECTRIC BLOWPIPE

Another process used for electric heating or welding is that which employs what is known as the *Werderman electric blowpipe*. In this process an electric arc is drawn between two carbon pencils, and the flame of the arc is blown against the work to be heated, in much the same manner as an ordinary blowpipe flame is used. The arc flame is blown, or deflected, by a small steel or electromagnet which repels the flame against the work. A blast of air may be used in place of a magnet, as it also will blow the flame to one side.

THOMSON PROCESS

By far the most common commercial process of electric welding is what is known as the *Thomson process*—so named after its inventor, Elihu Thomson. This method is about covered by patents. It is perhaps best described in the words of the literature issued by the Thomson Electric Welding Company:

> "The principle involved in the art of Electric Welding as invented by Elihu Thomson, is that of causing currents of electricity to pass through abutting ends of the pieces of metal which are to be welded, thereby generating heat at the point of contact, which also becomes the point of greatest resistance, while at the same time mechanical pressure is applied to force the parts together."

This method has one great advantage over other methods of heating for wēlding, and that is that the metal is heated from the inside and not from the outside.

When the pieces are brought together, the parts of the surfaces which touch are, of course, heated first; and as the heat increases, these parts become soft and flatten down, bringing other parts in contact. A curious fact in connection with this is that the welding temperature is regulated almost automatically. The surfaces which first come in contact serve as conductors of the current; and as the current passes through them, they become heated and gradually soften. As the temperature increases, the resistance increases, and these softened surfaces are gradually flattened out, allowing the cooler surfaces to come together. As the cooler points touch, being of a lower temperature, they offer less resistance to the passage of the current, which is thus automatically switched from the parts that have reached a "soft" heat to those that have not yet reached the welding temperature. This causes the joint to be brought to a uniform temperature throughout.

The heating is thus controlled by the softness of the metal as it flattens together under pressure; and when the union is completed, the soft metal begins to form a sort of burr around the joint, indicating that the weld is completed. The current is now turned off, for, if the heating were continued, the metal would be completely melted and the weld destroyed.

Probably the greatest proportion of defective welds, when welds are made in the forge fire, arises from the presence of some foreign substance between the surfaces. This may be due to oxidation of the metal itself, formation of slag from the flux, sulphur in the coal combining with the iron, or absolute dirt.

All of these factors tending to cause defects in welds are absent in the Thomson process. Since the metal is forced together as fast as it is heated, the heating being done first at the center, and extending outward, there is very little chance for oxide to form between the surfaces; and if any oxidation does take place, the oxidized metal is generally forced completely out of the weld when the pieces are forced together. The waste metal can be easily removed by trimming or grinding off the burr after the weld is completed.

Welds made in this way may be taken immediately from the machine, and hammered or worked in the usual way, to smooth up the joint. On small work, it is generally more practicable to smooth off the burr on an emery wheel.

The time required to make a weld by this process is very short, only a few seconds being required to join pieces as large as a half-inch or so in diameter.

Welds made by this method are considerably stronger than those made in the usual way. The strength of a good weld made by heating in a forge is about 75 to 80 per cent of that of the original bar, whereas, by the electric process, it is possible to make welds as strong as the bar

TABLE I

Metals, Alloys, and Combinations of Different Metals Welded by Thomson Process

METALS

Wrought Iron	Wrought Copper	Tin	Cobalt	Aluminum	Gold (Pure)
Cast Iron	Cast Copper	Zinc	Nickel	Silver	Manganese
Malleable Iron	Lead	Antimony	Bismuth	Platinum	Magnesium

ALLOYS

Various Grades of Tool Steel	Musshet Steel	Wrought Brass	Fuse Metal	Aluminum Alloyed with Iron	Silicon Bronze
Various Grades of Mild Steel	Stubs Steel	Cast Brass	Type Metal	Aluminum Brass	Coin Silver
Steel Castings	Crescent Steel	Gun Metal	Solder Metal	Aluminum Bronze	Various Grades Gold
Chrome Steel	Bessemer Steel	Brass Composition	German Silver	Phos. Bronze	

COMBINATIONS OF METALS

Copper to Brass	Brass to Wrought Iron	Brass to Tin	Wrought Iron to Tool Steel	Wrought Iron to Musshet Steel	Wrought Iron to Nickel
Copper to Wrought Iron	Brass to Cast Iron	Brass to Mild Steel	Gold to German Silver	Wrought Iron to Stub Steel	Tin to Lead
Copper to German Silver	Tin to Zinc	Wrought Iron to Cast Iron	Gold to Silver	Wrought Iron to Crescent Steel	
Copper to Gold	Tin to Brass	Wrought Iron to Cast Steel	Gold to Platinum	Wrought Iron to Cast Brass	
Copper to Silver	Brass to German Silver	Wrought Iron to Mild Steel	Silver to Platinum	Wrought Iron to German Silver	

itself, while a good average would probably be about 85 to 90 per cent of the full strength of the section.

Almost any metal or combination of metals can be welded by the Thomson process, as the range of temperature through which the metal is soft enough to weld has little effect on the welding. As the pieces are forced together instantly as soon as soft, a metal which melts with almost no preliminary softening can be successfully handled. Results obtained in actual practice by the use of the Thomson process in the welding of metals and alloys, are shown in

Table I, compiled by Mr. Hermann Lemp and recently published in *Engineering Magazine.*

Direct Method. On experimental work, when the process was first used, what is known as the *direct method* was employed. The apparatus used consisted of a generator, with clamps to hold the pieces to be welded fastened directly to the generator frame. The machines used were low-voltage dynamos much the same as are now used for plating work. While such a machine may be fairly satisfactory for experimental work in the laboratory or for very light work in a clean shop, it has many unsatisfactory features when used for large work on a commercial scale. It is, of course, hardly practicable to carry a heavy current of low E. M. F. (generally less than 5 volts) for any distance, as the loss in power through resistance would be enormous, and the cost of the heavy copper conductors would make the process too expensive in installation.

The above difficulties have developed what is known as the *indirect process.*

Indirect Method. In this method the power is taken either from the distributing circuit of a central station, or from a central generator in the shop. The current is carried to the point where the welding is to be done, at a comparatively high-voltage, and a transformer is then used to step down to the required E. M. F. This transformer, as it has no moving parts, is generally carried in the base of the welding machine, with the welding grips, as close to the secondary coil of the transformer as possible.

The apparatus commonly used consists of the following:

An alternating-current generator, or some source of central power.
Some regulating apparatus to control flow of current.
A static transformer to reduce the voltage.
Suitable mechanical arrangement to clamp and force the pieces to be welded together.

A typical plant is outlined in Fig. 4, consisting of generator, regulator for current control, switch for turning the current on and off, transformer for increasing the amperes and lowering the voltage, and clamps for holding the pieces to be welded.

In welding of this character, it is the number of amperes (or current strength) which is the important factor; and only a sufficient voltage (or pressure) is maintained to force the current through the work. The object of the low voltage is, of course, to cut down the amount of power required. This may be easily seen from the following: Suppose that a certain weld requires a current strength of 10,000 amperes, and assume that the generator delivers current at a voltage of 100. Now, if a transformer be used to reduce the voltage to 10 volts, and assuming no loss in any of the apparatus, the power used will be:

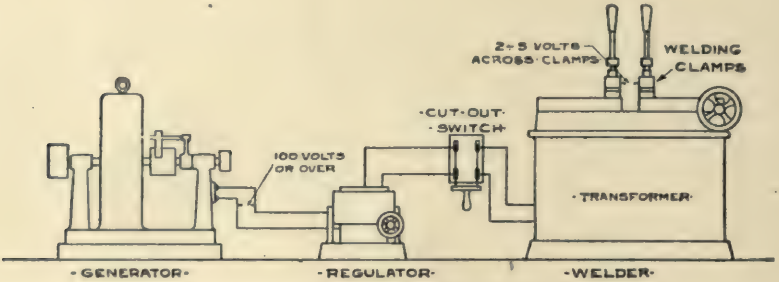


Fig. 4. Electric Welding Plant, Indirect Method.

$$10{,}000 \times 10 = 100{,}000 \text{ watts;}$$

and the power delivered by the dynamo being the same, the *amperes* delivered by the dynamo will be:

$$100{,}000 \div 100 = 1{,}000 \text{ amperes.}$$

Now, if a transformer be used which reduces the voltage from 100 to 5, instead of from 100 to 10, the power used would be:

$$10{,}000 \times 5 = 50{,}000 \text{ watts;}$$

and the amperes delivered by the dynamo will be:

$$50{,}000 \div 100 = 500 \text{ amperes,}$$

this being just half of what it was in the first case. It will be seen from this, that for economical operation the voltage should be reduced as far as possible. It should be remembered that when working with *alternating* current, the power used cannot be taken as the direct product of the volts and amperes, a more complicated calculation being necesary; but the principle illustrated above still holds good.

A diagram of a very simple type of transformer is shown in Fig. 5. The primary or high-voltage coil is that on the outside, and is wound of fine wire; while the secondary or low-voltage coil consists in this case of one single, straight conductor with the terminal connections fastened to the ends. As mentioned before these terminal connections to the welding clamps should be as short as possible, on account of the low voltage.

The current is controlled by a cut-out switch and resistance placed close to the transformer on the primary circuit. In some of the later machines, the cut-out switch, as well as the mechanical means used to force the pieces together, is controlled automatically.

The transformers are substantial in construction; and as there are no moving parts, there is little chance of anything getting out of order. The pieces to be welded are held in suitable clamps which form the terminals of the secondary coils. These clamps are mounted on a slide which allows them to travel back and forth. The pieces to be joined are fastened in the clamps, and the current turned on. The metal is heated at the joint, and gradually softens as the heating is continued, the pieces being forced together by means of a hand-lever, or automatically by the machine itself. When the weld is completed, the current is turned off, and the work taken from the clamps.

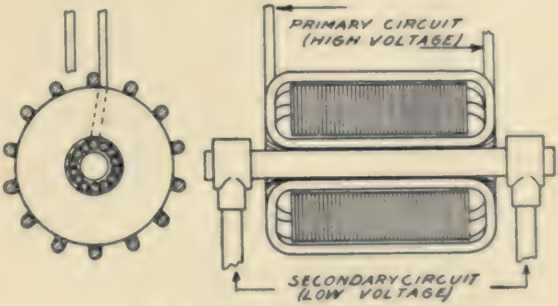


Fig. 5. Simple Transformer.

A simple machine which was used for some experimental work, is shown in Fig. 6. The current used in this particular case was taken from the lines of the Edison Company at 220 volts, and was reduced in the transformer to 5 volts. It will be noticed that the clamps are so shaped that the work may be instantly released when the weld is completed, taken from the machine, and the burr hammered smooth on an anvil if necessary.

No very great care need be taken as to the insulation on the machine itself, as, at the very low voltage used, there is very little chance of current leakage. The bed of this machine was cast iron; and contact was made by bringing the terminals of the transformer up through the base of the machine, and resting small blocks of copper on them, to which the pieces to be welded were clamped.

The principal factor of cost in a machine of this kind is the copper in the transformer. In the machine in question, the copper terminals were 1 by 1½ inches in section; but, as the capacity of the clamps was far less than this, the terminal connections to the clamps were made only about one-quarter this size.

For purposes of experiment, it is possible to make a weld by simply clamping the pieces which are to be joined to the terminal wires of a transformer, by means of wooden hand-screws, and forcing the pieces together with the clamps. It is even possible to use iron clamps without danger to the operator, there being no chance of shock at such a low voltage. In fact, in designing a machine, there is no need to insulate the machine from the operator, for the reason given above. This however does not apply to the high-voltage side of the transformer, which should always be fully protected. On the operating side of large machines, a hand may be placed on each of the terminals when the full current is on, and no shock or sensation felt.

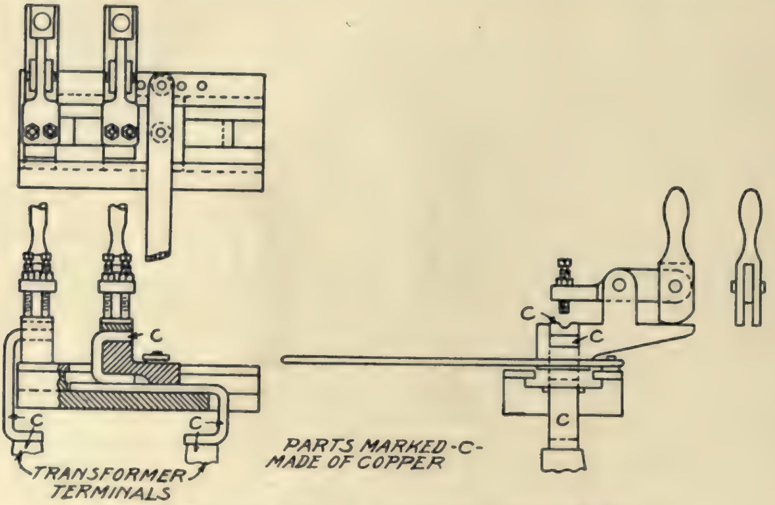


Fig. 6. Diagram of Simple Apparatus for Electric Welding.

Fig. 7 shows a cut of a simple commercial welder. This is what is known as a hand-machine, as the turning on and off of the current, and forcing of the pieces together, is done entirely by hand. As shown in the cut, the weld has just been completed, and the finished piece is still in the jaws. The machine is so arranged that by throwing the clamping levers when the weld is completed, the work may be instantly released. To adjust the clamps for different thicknesses of work, the adjusting screws are used; these are shown on top of the clamping jaws, and also just underneath the clamping levers at the back of the machine. The pieces are forced together by means of the long lever and hand-wheel at the right of the bed-plate. The hand-wheel is used for quick adjustment, and the lever for the final *squeeze* that does the welding.

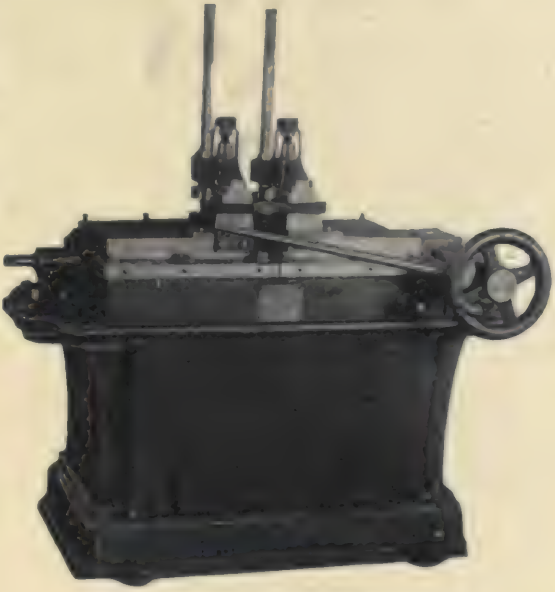


Fig. 7. Simple Commercial Welder.

This machine is largely used for straight and miscellaneous work; has a maximum capacity of 1.23 square inches of iron or steel, or .40 square inch of copper; and requires, at a maximum, 35 horsepower for 60 seconds.

The transformer is placed in the heavy bed of the welder, as in this way the conductors carrying the welding current to the jaws are made very short, to reduce the current loss to a minimum.

In operation, the pieces to be welded are placed in the clamps, and brought close together by the hand-wheel, the current being next turned on. In a few seconds the pieces become hot at the weld; and as soon as soft, they are forced together by the long lever, and the current turned off. On large work the piece is then instantly taken from the machine, and the joint smoothed up, either in the usual way on the anvil, or between suitable dies on a drop hammer. The work is done very rapidly, and the whole operation on a comparatively large piece may be done in two minutes. The time required on small work is only a few seconds, including the entire process.

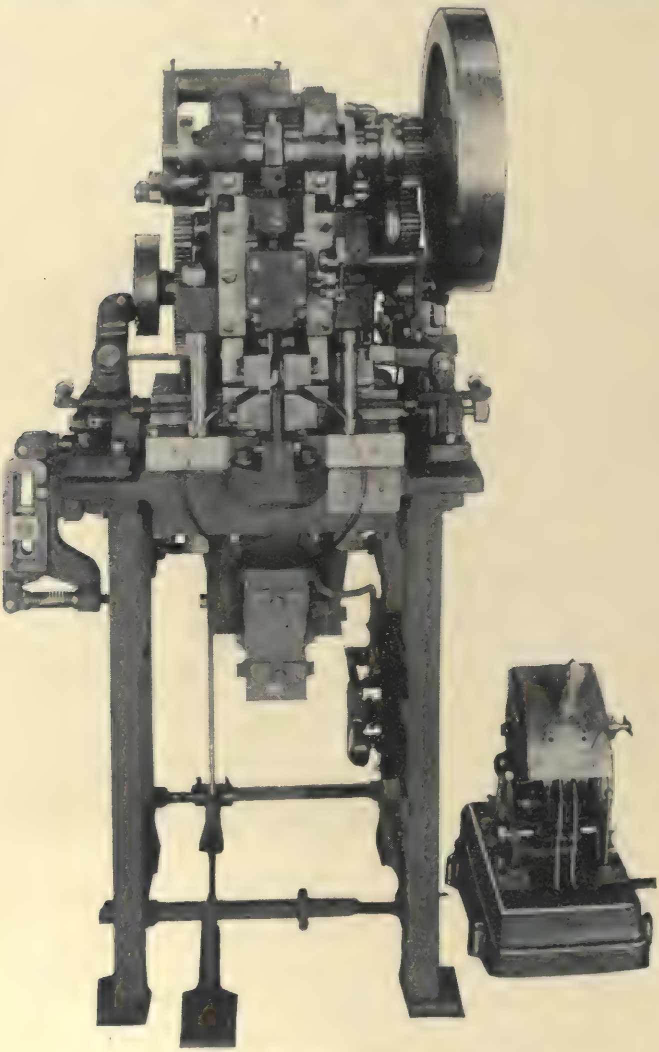


Fig. 8. Automatic Electric Welding Machine.

For work where many pieces of the same kind are to be welded, a machine may be used which will work automatically. This is of decided advantage in addition to the speed, as the pressure on each weld may be kept uniform and controlled exactly, and the welds in this way made all the same. It has been found that welds which would be almost impossible to make on the hand-machine are easily made with the automatic, as the pressure control in the latter is much more exact. This advantage is most marked on metals which are very crumbly at high heats, and on small and delicate work.

A machine of this type is shown in Fig. 8. Some of these machines not only take care of the actual welding, but also have dies or jaws which press and form the joint to the same shape and dimensions as the bar stock, thus serving the combined purpose of heating and shaping.

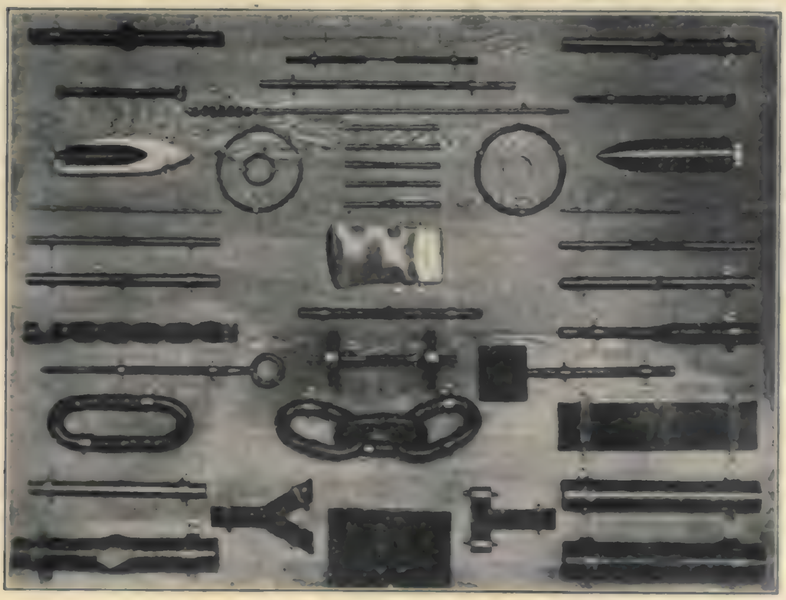


Fig. 9. Examples of Machine-Made Welds.

One of the common uses that a machine of this sort is put to is that of making barrel hoops. These are made of wire about $\frac{3}{16}$ inch in diameter; and as they are intended for rough use, no effort is made to smooth up the joint. From 300 to 800 welds of this sort may be made per hour, and the machine operated by a boy. The average for wire hoops is about 500 per hour, according to figures given by the manufacturers of the apparatus.

Figs. 9 and 10 show examples of various kinds of welds made by this process—from small wires to large bars.

The shape of the piece has very little to do with the welding, so long as the pieces have the same section at the weld. I-sections and work of that character which it is impossible to handle in the ordinary way, can be worked as easily as round or rectangular bars. The weld of a clincher rim, shown in Fig. 11, is a good example of the ease with which difficult work can be handled. The cut shows the piece with the burr still left on the weld, which is afterward smoothed or ground off, a uniform surface being left.

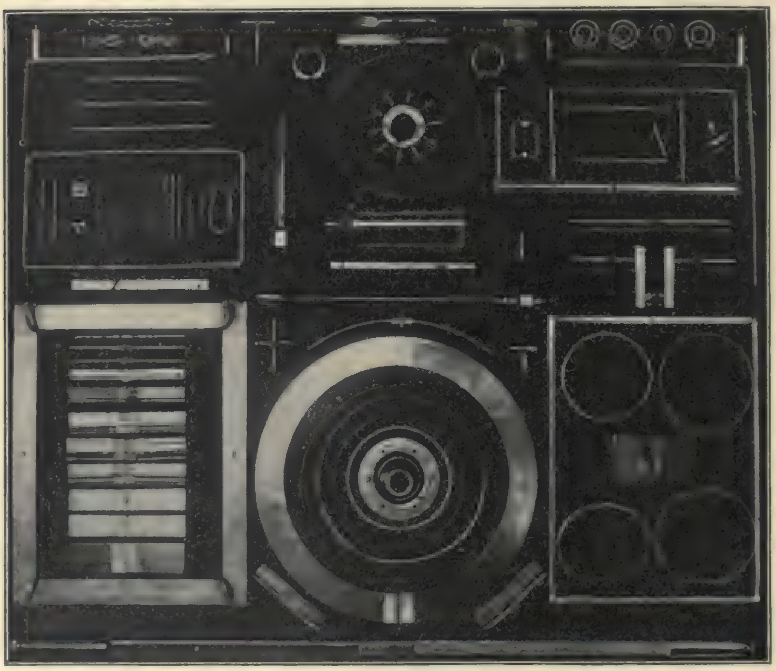


Fig. 10. Examples of Machine-Made Welds.

On small work where the joint is wanted smooth, the burr is generally removed with an emery wheel, unless the operation is performed in an automatic machine, in which case the burr is taken care of by the welder itself.

Practically all the welds made on the machine are butt welds; and while no particular preparation of the ends is necessary, still it is always best to see that they touch each other as near the center as possible.

Fig. 12 illustrates the action of the pieces in welding. In *A* are shown the pieces ready for the heating. It will be noticed that the ends are slightly convex in order to bring the centers in contact first. *B* shows the pieces as they appear when the weld is about half-completed, the shaded portion showing about the length that is ordinarily heated by the action of the current. *C* shows the completed weld, the shaded portion still representing the extent of the heating.

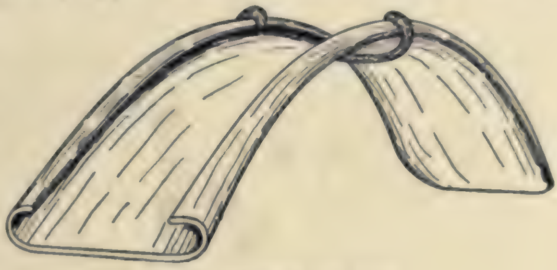


Fig. 11. Clincher Rim Weld.

One of the noticeable characteristics in connection with electric welding is the short distance from the joint that the work is heated. The actual heating effect of the current is confined almost entirely to the weld; but of course there is some heating by conduction which raises the temperature a short distance from the joint. This heating effect does not extend very far, as the time is so short that the heat does not have a chance to travel much. On a piece ¼ inch in diameter, the bar may be grasped with the bare hand within an inch of the weld immediately after the welding is completed.

On account of the above conditions, many machined and finished pieces may be welded without distortion, very little effort being required to refinish the part heated in welding.

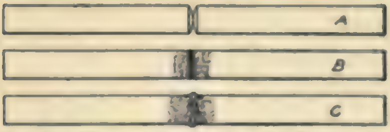


Fig. 12. Illustrating Action of Pieces in Electric Welding.

In welding in this way, it is always an advantage to have the pieces of as near the same section as possible at the weld. For instance, it would be a rather difficult matter to weld a bar of very small section directly against a bar of large cross-area. A method of handling work of this character is shown in Fig. 13, where it will be noticed that a sort of lug or projection has been left in making the main forging, to which the piece of smaller section is welded.

The difficulty of this sort of welding is largely due to the fact that the bar having the larger section will of course radiate the heat faster, with the result that the smaller bar will become overheated and burn long before the larger bar is hot enough to weld. This is overcome to some extent by so clamping the pieces that the piece having the larger section will project farther from the clamp jaw than the smaller one does. This will overcome a small difference of section; but when the difference is great, the larger piece should have its section reduced to that of the smaller for a distance of about one-quarter inch at least.

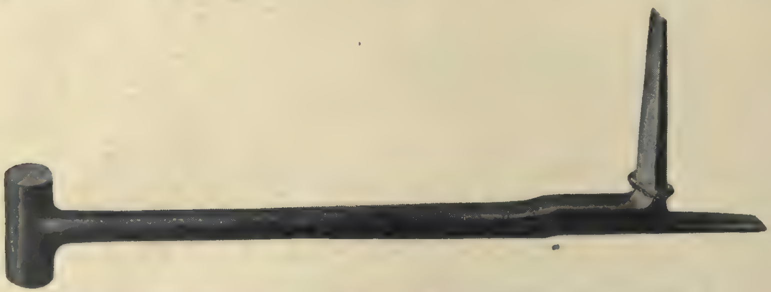


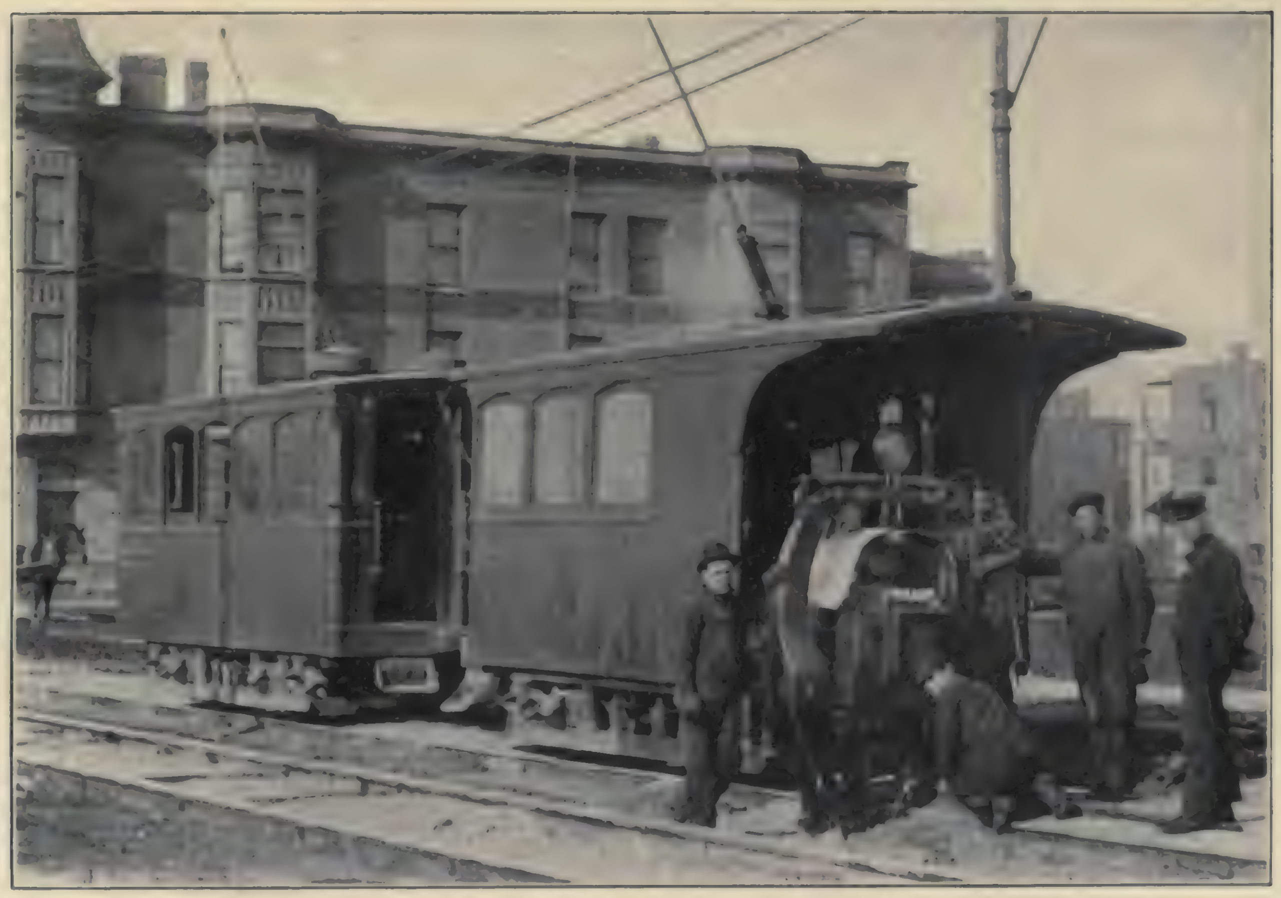
Fig. 13. Illustrating Method of Welding Pieces of Different Cross-Section.

On heavy work it is necessary to force the pieces together with hydraulic pressure, it not being practicable to obtain the pressure with hand-levers. In fact, in some machines the gripping also is done in this way.

When welding tin, lead, zinc, etc., the pieces do not become hot enough to emit light or become incandescent, and the softening of the metal must be taken as an indication of the welding temperature. Lead pipe can be satisfactorily welded if care is taken in preparing the ends, which should have the edges beveled in order to reduce the section that is being heated.

Lead pipe of a comparatively large section can be handled, lead offering considerably more resistance to the passage of the current than either iron or copper. As a general rule, it is easier to weld electrically materials which have a comparatively high resistance than those of low resistance; thus copper requires more current than either iron or steel; iron or steel, than lead; etc.

One of the interesting applications of electric welding is the



ELECTRIC WELDING OF RAILS IN STREETS OF CHICAGO
Bar is Clamped to Rails and Welded by Current from Trolley.

making of continuous cables of both steel and copper. This is easily done, and the strength is very little diminished by the process. Of course the cable is left solid at the point where the weld is made, as the metal is completely fused into one solid lump; but as this extends for a short distance only, scarcely equal to the diameter of the cable, it is no very serious objection.

Chain and Ring Welding. Chain links are welded by this method, although it would seem that the body of the link, being solid, would offer less resistance to the current than the joint, with the result that the current, following the path of least resistance, would heat the body of the link and leave the joint cold. This however is not the case, as the grips may be placed close to the joint, thus lowering the resistance across the weld and increasing the resistance through the solid metal.

Another fact is that while an alternating current follows the path of least resistance, it also tends to take the shortest path or the path of least counter-induction or self-induction, and will not go around a ring as easily as across the straight joint. The flow of current around the solid part of the ring may be still further checked by placing in the center of the ring or link a magnetizable iron core, effecting a greater counter-induction force.

Track Welding. This is one of the most important of the developments of the electric welding industry. Various methods of making rails continuous have been tried, but the most satisfactory seems to be that of electric welding. As nearly all of the street-railway and interurban work is now electric traction, the problem of a satisfactory track must be considered from the electrical as well as from the mechanical side. In other words, the track must not only present a smooth unbroken path for the wheels in order to have the cars run smoothly, but the rails must also be so bonded together as to make a continuous electrical conductor. The joints must have the same conductivity as the solid rail, or a greater conductivity.

One of the earlier ways of accomplishing this was to cast a chunk of cast iron around the joint, completely enclosing the rail with the exception of the head, for a distance of 8 or 10 inches. The objection to this was that the body of hot metal around the rail in the casting process so heated the head of the rail that is was annealed and softened enough to cause excessive wear, and was soon worn down enough in the immediate neighborhood of the joint to cause the cars to *bump* when passing over.

These objections were satisfactorily met by the electric weld; and this process is now almost universally used for rails buried in city streets, and to some extent on trackage on interurban lines.

Special apparatus is used for this work, and what is known as a *welding train* employed. The welding is generally done under contract by a firm having the special equipment for the purpose, and not by the railroad company itself. The contractors clean the ends of the rails to be welded; *shim* the joints where necessary; make the weld; and grind down the head of the rail to a smooth, even surface after the weld is made.

Welding Train. The welding train generally consists of four cars. The first car, taken in the order in which they operate, is the car carrying the sand-blast apparatus. The next two cars are the car carrying the welding machine proper, and the transformer car. The fourth car is the one carrying the apparatus for grinding the rail down to a smooth joint.

The operation of welding is briefly as follows

The street, around the rail, is opened up for a distance of about two feet each side of the joint, making a hole about four feet long and two feet wide each side of the rail. The old fish plates and bonds are then removed, and the sides of the rail cleaned with the sand-blast apparatus to remove all scale and dirt. If there is any opening between the rail ends, this is now filled by driving in shims made of thin *slices* of rail of the same section as that to be welded. The welding cars then take up the operation.

The plates to be welded to the sides of the rail are clamped in place, and the jaws of the welder are adjusted in position. The current is then turned on; and when the metal is hot enough, the weld is made by forcing the jaws of the welder together with hydraulic pressure.

When the weld is completed, the current is turned off; but the pressure is kept on the joint for a short time, in order to hold the plates in position while cooling. This operation is repeated until the three spots on the plates are welded to the rail. The welder then moves on to the next joint, and the grinding car completes the work by grinding off the top of the rail to a smooth, flat surface.

The sketch in Fig. 14 will give an idea of the sort of joint that is made by this method. A plate about an inch thick is welded each side of the rail, the welding being done at three spots only, at about the locations shown by the dotted lines, one at each end and one in the center.

Fig. 15 shows the diagram of a sand-blast car which carries a motor for running an air-compressor, the air-compressor itself, and the storage tank containing the sand under air pressure. The motor used in one car, fitted up for this purpose, and used in Chicago by the Lorain Steel Company, was of 18 horse-power; and 20 pounds pressure was carried on the sand tank. The sand was forced from the tank and through a flexible hose, and directed against the joint by a small nozzle. The work of cleaning the joints was quickly done, and the labor of only one man was required to take care of the car and apparatus.

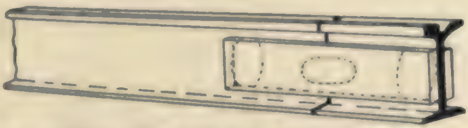


Fig. 14. Illustrating Process of Welding a Rail Joint.

As the current in most street-railway work is continuous, it is necessary to use a *rotary converter* to obtain power for the welding transformer. In the case mentioned above, the apparatus used consisted of a General Electric rotary converter. Current was taken from the trolley wire at about 600 volts, and delivered from the converter as alternating current, 40 cycles, at about 280 volts.

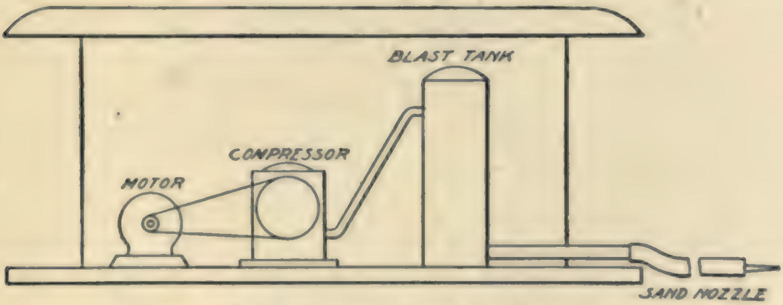


Fig. 15. Diagram of Sand-Blast Car.

From the converter the current was carried through a potential regulator of 60 to 65 kilowatts capacity.

At this voltage the current was carried to the welding transformer placed between the arms of the welding machine. This machine is shown in Fig.16, which illustrates the machine proper detached from the car. In Fig. 17 is shown a sketch of this welder, with a short explanation of the parts. The high-potential current is carried directly to the welding transformer, and the voltage is here reduced to about 6 volts. Probably the current used at the grips is about 20,000 amperes. In the car with the welder are also motors and fans used for circulating the water through the copper grips in order to keep them from being overheated, and also for cooling the circulating water. There are also motors for raising and lowering and shifting the welding machine. The circulating water is cooled with a fan. The welding machine is carried on a sort of crane controlled by a long screw, and may be shifted to bring the grips in the proper place over the joint to be welded. The shifting of the welder is done mostly by power furnished from the motors in the welding car.

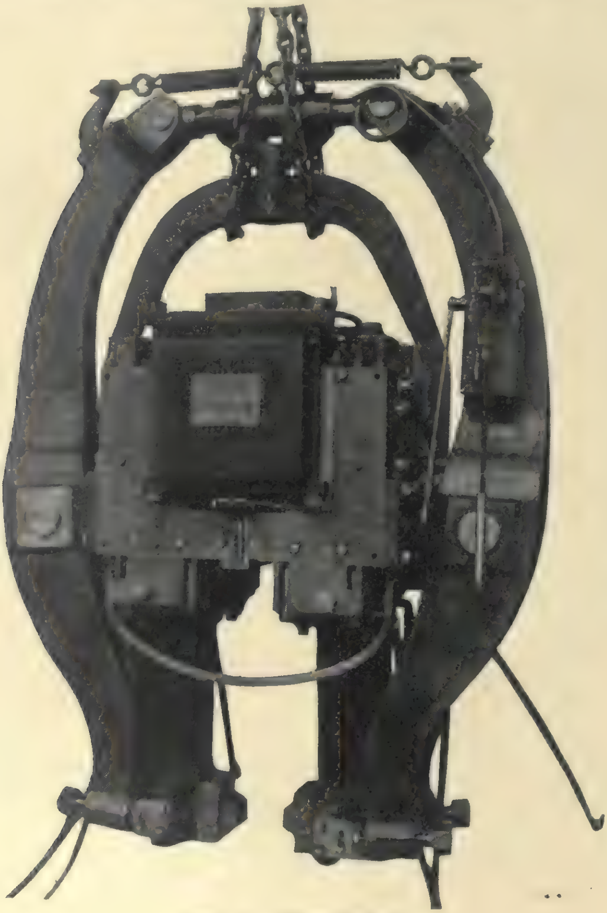


Fig. 16. Electric Welder.

In Fig. 18 is shown a complete welding train in operation, the sand-blast car at the left, the grinder car at the right, and, in the center, the two cars containing the transformer, the regulating apparatus, and the welding machine proper. The welder may be tipped back or elevated to clear the rail while the car is being moved forward to position for another joint. The welder itself is shown separately in Fig. 19. Fig. 20 is a separate view of a sand-blast car; and Fig. 21, a separate view of a car for joint grinding.

Each of the cars of the welding train—with the exception of the transformer and welding cars, which are run together as one car—is equipped with an ordinary motor, and runs separately as a trolley car in moving from place to place.

In making the weld, the car is brought to position, and the plates adjusted. This must be done with care, or a bad weld will result, as will be noted later. Clamps are then put on to hold the plates in the proper position, the welding clamps are gripped over the plates, and the current turned on. The heating is watched; and as soon as the plates become red-hot, a flux is sprinkled on the joint. When the heating has continued far enough, the jaws are forced together with the hydraulic pump and plunger arrangement, between the upper ends of the arms. The pressure brought to bear on the joint is about 40 tons. The piston area is about 10 square inches; the pressure on the piston, about 4,000 pounds per square inch; and the leverage of the arms, about 2 to 1—making the direct pressure about as given above. Fig. 22 is a photograph of a completed weld.

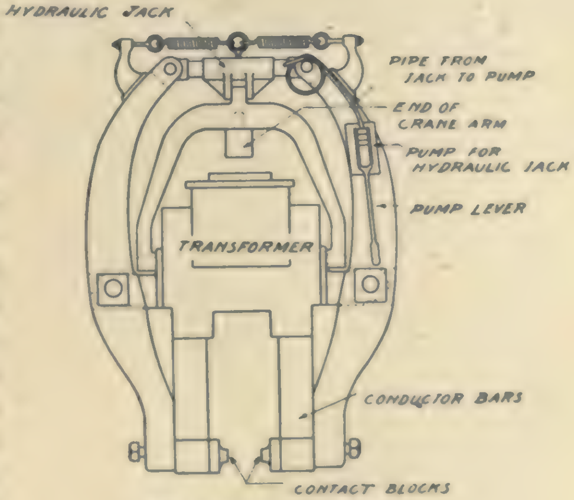


Fig. 17. Diagram of Welder.

The plate used on the side of the rail is shown in detail in Fig. 23.

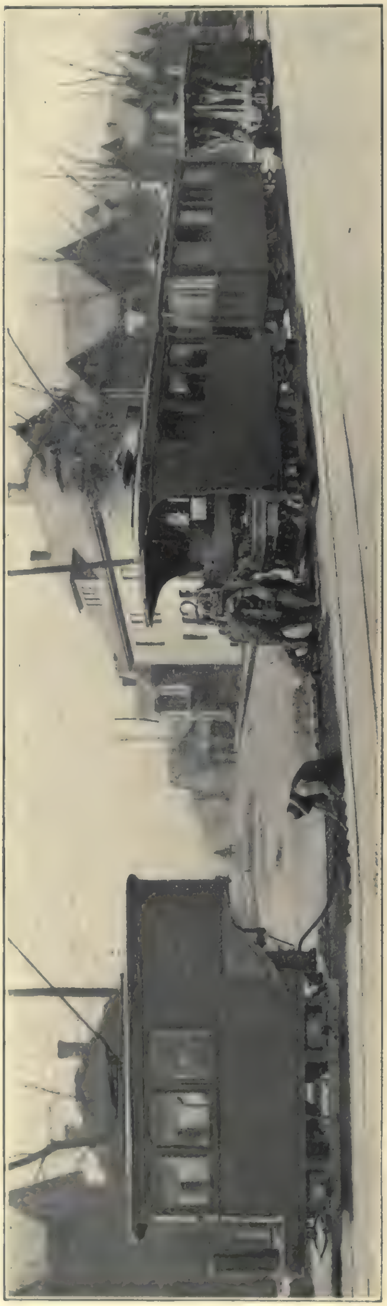


Fig. 18. Electric Welding Train in Operation. Lorain Steel Company, Johnstown, Pa.

The dimensions are 22 inches by 4 inches by 1 inch, the last being the thickness. The plates are uniform in thickness, with the exception of three *contact-points* raised on them, one at either end and one in the center, the object being to concentrate the heating at these points. It will be noticed that these points are not flat, but are stepped, still further concentrating the effect of heating at the start of the welding process. When the weld is completed, these spots have been flattened out so far that the bar is brought in contact with the rail web. In a finished joint, there is about 30 square inches of welded surface on both sides of the rail.

Care must be taken to see that the ends of the plate are matched up on the two sides of the rail, or the twisting action of the welding pressure will cause the weld to crack open in cooling. On one occasion, in connection with work of this character, observation showed that defective welds were resulting, and it was discovered that the ends of the weld plates extended beyond the ends of the welding surfaces. In other words, instead of ending at the welding spot as shown in Fig. 23, the weld plates extended for a short distance beyond, as shown in Fig. 24. As this distance was not uniform, and as the plates were placed by bringing their ends even, the result was that the welding spots were not brought opposite each other, and a sort of twisting action took place, causing the welds to crack open occasionally. When this was discovered, the ends of the plates were trimmed off to a uniform length, and no further trouble resulted.

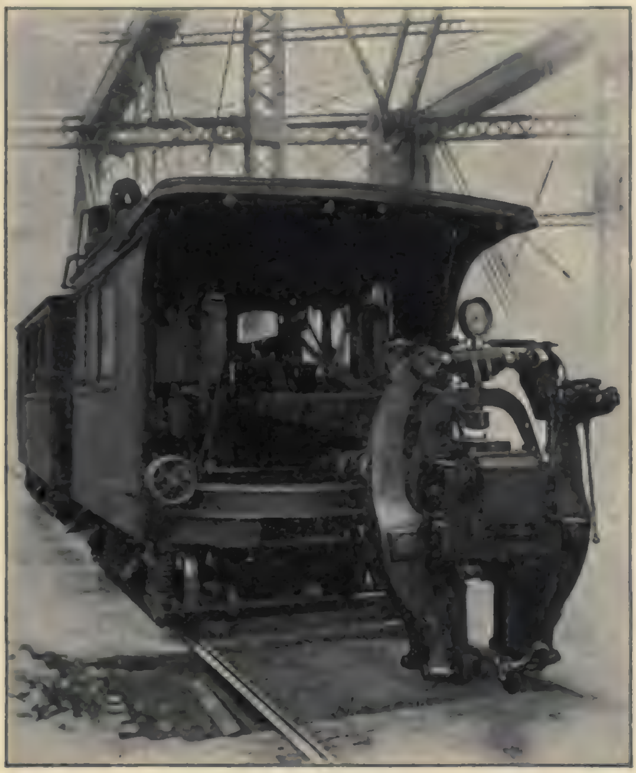


Fig. 19. Welder Car.
Lorain Steel Company, Johnstown, Pa.

The effect of placing with uneven ends is shown in Fig. 25, where the ends are placed in line, thus throwing the lugs out of true.

The *actual* time required for welding—that is, the time the current is on—is about 2½ to 3½ minutes for each point of contact, of which there are three at each joint; the variation in time being largely due to fluctuations in the line current, which, as it is taken from the trolley circuit, varies to some extent. On end welds, the clamps are kept on under pressure for three minutes after the weld is made and the current turned off. The center weld is clamped in this way only one minute. Such cooling under pressure was found necessary to insure good welds. When the clamps were released immediately after the current was turned off, it was found that frequently the weld would crack open in cooling, making a very large percentage of bad welds.

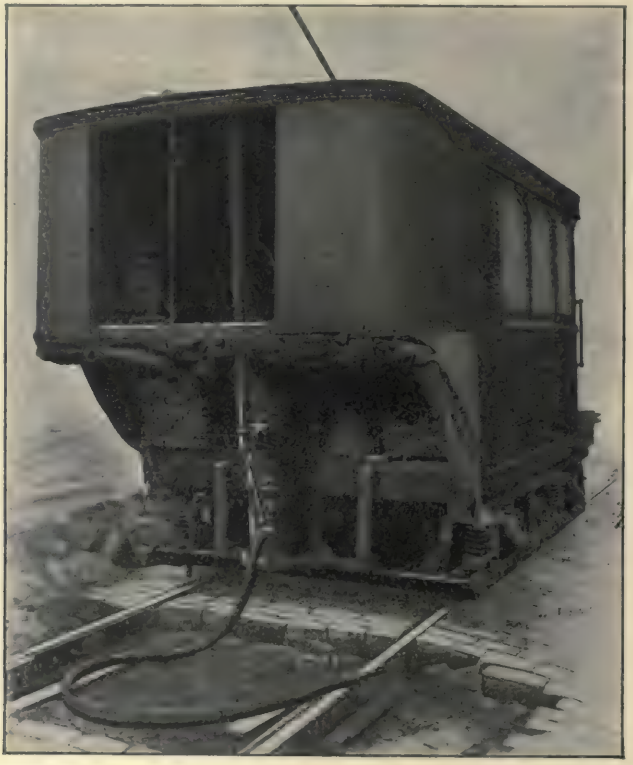


Fig. 20. Sand-Blast Car. Lorain Steel Company, Johnstown, Pa.

The heat is so localized that the head of the rail is never red-hot during the entire process, with the result that it is not softened, and

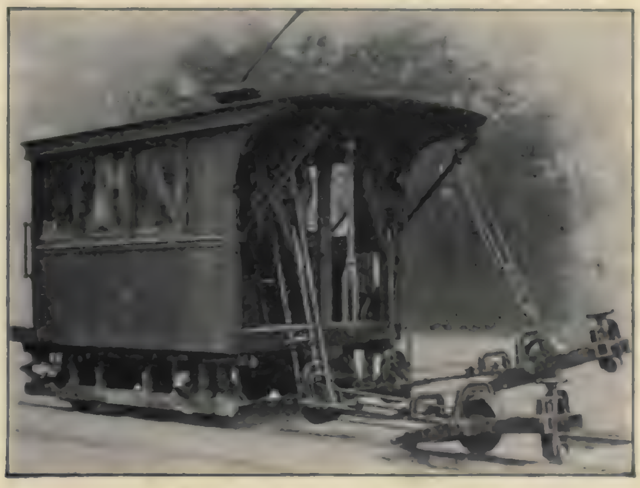


Fig. 21. Car for Joint Grinding.
Lorain Steel Company, Johnstown, Pa.

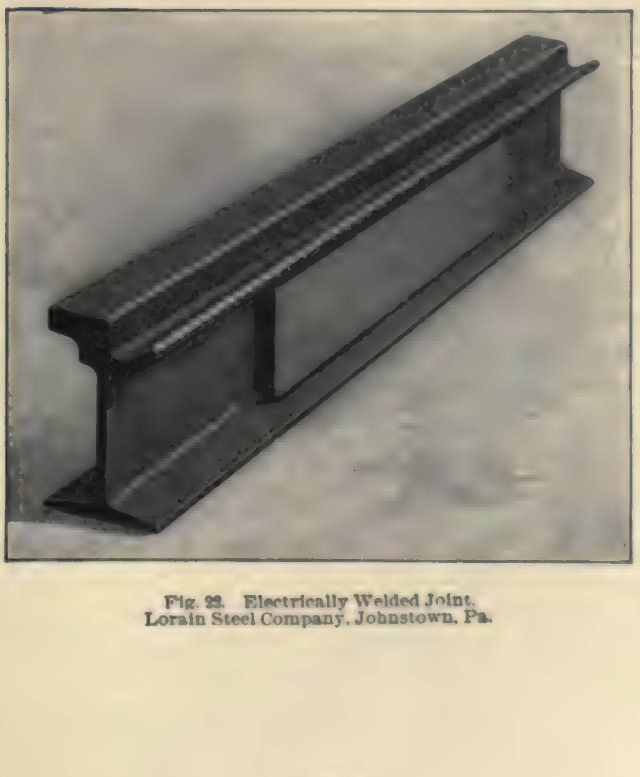


Fig. 22. Electrically Welded Joint.
Lorain Steel Company, Johnstown, Pa.

excessive wear does not take place at the joint, as is liable to be the case with the old method of cast welding.

The welds here illustrated were made under contract, the contracting company furnishing the welding train and men, the railroad company furnishing the current. The usual charge is $5.25 per joint, the welding company to replace any welds proving defective within one year. The percentage of good welds is over 99 per cent. This price seems to be practically universal but a slight difference is sometimes made in the terms for replacing defective joints, in some cases the welding company agreeing to pay back about twice the original cost of the weld for every defective joint.

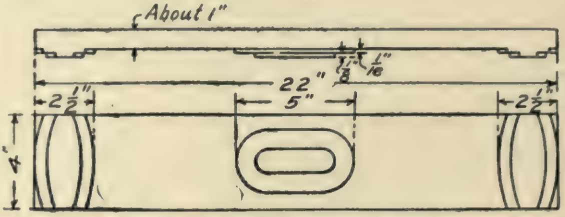


Fig. 23. Plate Used in Rail Welding.

The welds are finished by grinding with the portable grinding rig carried on a separate car. The arrangement of this car is shown in Fig. 26. A 5-horse-power motor is attached to each grinder, one on each side of the car. Each motor runs its own grinder only. The emery wheels are about 14 inches in diameter, with a 2-inch face, and are adjusted with the screws as shown. It requires from 5 to 10 minutes to dress the rail down to a smooth, even surface. The leveling is done with a straight edge. The grinder is so fixed that it may be moved back and forth on the rail, the grinding wheel being raised or lowered by means of the adjusting screw on the front end of the carriage. The jointed frame keeps the belts tight and allows the forward and back motion, at the same time preventing much movement sideways. One motor only at a time is used.

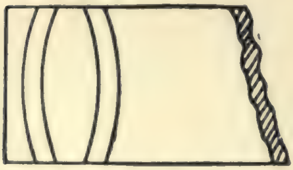


Fig. 24. Weld Plate Extending Beyond Joint.

There is another process of rail welding, in which a liquid flux is used. This process has been experimented with, but has not yet been perfected. A mould is clamped around the joint; the current is turned on; and the flux, which has previously been heated and melted in a crucible, is poured into the mould. Welding clamps similar to those used in the Thomson process are employed, and plates are welded to the side of the rail in much the same manner. This process, in fact, is much the same as the Thomson, except that a slightly higher voltage is used, a melted flux is employed, and the welding grips are surrounded by a mould to hold the molten flux in place. The inventors claim that less power is required, and that work may be done more cheaply than by the Thomson method. In the experimental car used, the transformer for the final reduction in voltage was placed in the car itself, and the low-voltage current carried through wires to the welding grips. A large switchboard was provided in the front end of the car, equipped with means for changing the voltage at the grips, as a constant voltage was not used throughout the process.

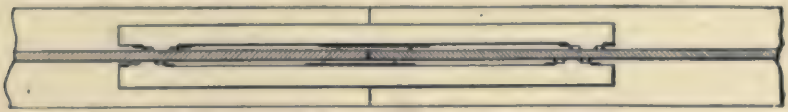


Fig. 25. Showing Effect of Uneven Placing of Plates.

Rail Welding Labor and Costs. The schedule given below shows approximately the labor required to run the welding train, including the cleaning of the joint with the sand-blast, shimming, actual welding, and grinding of the finished weld. Two gangs are used, one day and one night; but only one foreman is used to look after both gangs. For one gang only, including the foreman who takes care of both gangs, the schedule of labor is as follows:

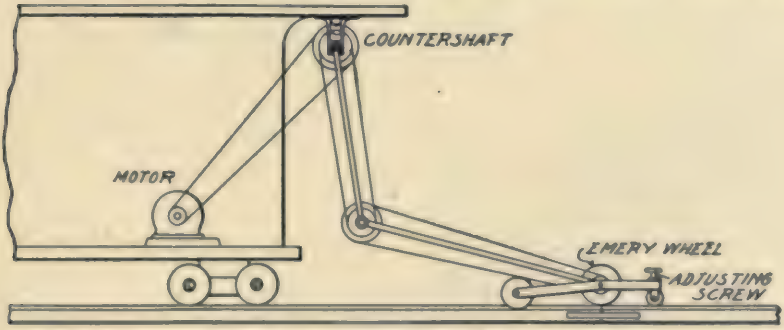


Fig. 26. Diagram of Grinder Car.

1 Foreman.
1 Sand-blast man.

1 Welder man.
2 " " helpers.
1 Dynamo man.
1 Grinder man.

This makes a total of 13 men for both day and night gangs, which force of men will make about 70 to 75 joints of three welds each per day.

The dynamo man is stationed in the transformer car, where instruments are provided for keeping track of the voltage, power used, etc. This man also keeps track of the time on the welding, signaling the welder when to release the grips after the weld is completed. The turning of the current on and off is done by the men at the welder.

The time on each joint is about 19 minutes, each weld requiring about 6 minutes, a minute more being taken to move from joint to joint.

Mr. P. Ney Wilson* gives the following data of some work done in New Jersey. The welding was done by the Lorain Steel Company, at a contract price of $5.25 per joint for the welding alone.

In figuring the cost to the railway company for opening the street around the joints, and relaying the pavement after the welding was done, the labor cost is taken as 15 cents per hour—or rather, the labor has been calculated to this average basis per hour. Rails were of 7-inch girder type similar to Cambria No. 824; number of men employed, 98; joints per day, 64; data taken from about 3,000 joints; street opened up in each case, and returned to original condition after weld was made.

Cost per joint—(average results on over 3,000 joints):

Preparing joint, opening street, etc.		$2.277	
Material (saws, tools, etc.)		.188	
	Total		$2.465
Credit for scrap (old bond, etc.)			.912
	Net cost		$1.553
Replacing asphalt			.832
Contract price for weld			5.25
Net cost per joint completed			$7.635

The credit made above for scrap includes the amount realized from the selling of the old fish-plates, copper bonds, etc.

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* *Engineering—Contracting.* March 20, 1907.

On some other work the same author gives the following:

7-in. girder rails, 60-ft. lengths, Penn. Steel Co. No. 238 and Cambria No. 824.

Pavement, Belgian block on sand foundation.

Average number of men employed, 103.7, at 15 c. per hour.

Cost of fitting joint for welding after deducting credit for scrap, $1.433

On another street where same rail was used in 30- and 60-foot lengths:

84.6 men, 15 c. per hour.
Average joints per day, 60.
Gross cost of fitting for each joint, $2.292.
Net " " " " " " $1.382.

This same joint was also used on some interurban work near Providence, R. I., where the rails were exposed to the air; but in this case an expansion joint was used about every 1,000 feet. The track was laid with T-rail, and was about six miles long.

Wire Welding. On telegraph wire, the Roebling Company are reported to make, on an average, about 600 welds per day. A large portion of the time, however, is taken in handling the heavy coils of wire.

Small wire loops and steel rings are made by the Thomson Company at the rate of from 1,000 to 3,000 per day of ten hours.

Direct and Alternating Current. On small work, direct current may be used; but for heavy pieces, there is a decided advantage in alternating current. The final results obtained are about the same whether direct or alternating current be employed; and in fact a storage battery may be used, if designed for very rapid discharge.

Nearly all welders are built for alternating current, the reason being that the heaviest current is carried on or near the surface of the conductor; and as it is here that the greatest radiation takes place, the useful heating effect of alternating current is thus greater than that of direct current of the same strength.

It is theoretically possible to weld sections of any size with a small current; but in practice it is found that the rapid radiation of heat from the surface of the metal must be taken into account. On large work, when a small current is used, a point is reached where the radiation will equal the heating effect of the current, and then the temperature remains constant. When this is the case, the remedy is to use a greater current strength.

Heating in Welder. The same process that is used in welding may be employed in any heating operation. Pieces are sometimes heated between the clamps of the welder, and upset to form a sort of ball or collar, as illustrated in Fig. 27. The same method is also used to fasten collars to shafts by a sort of riveting. The collar is made a loose fit on the shaft, and is slipped on into position, the shaft being then gripped in the jaws of the machine in such a way as to bring the collar midway between the two. The shaft is heated, and, when the pressure is applied, is upset tightly into the hole in the collar and against the sides, somewhat as shown in Fig. 28, thus firmly clamping the collar in place.

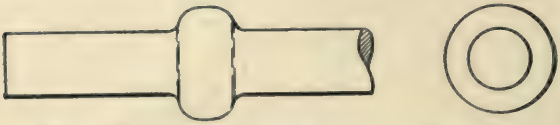

Fig. 27. Ball or Collar Formed at Joint of Electrically Heated Pieces.

Where it is desired to heat only the end of a bar, the submersion method may be used; but when the center of a bar is to be heated, the Thomson process is the better. In the latter case, the bar is gripped in the clamps in the usual way, with the part to be heated between the two jaws; the current is turned on; and the heating is continued until the metal is raised to the desired temperature, when the current is turned off, and the bar taken from the machine and treated in any way desired A bar may be heated at one end only, in a Thomson welder, by gripping the piece in one jaw and butting it against a much heavier piece held in the other jaw. The heating will be confined almost entirely to the smaller bar if there is a large difference in section between the two.

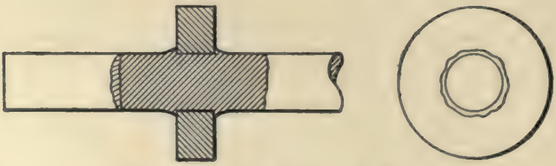

Fig. 28. Collar Fastened to Shaft.

Brazing and soldering may be done in this same way; but of course the amount of heat used is very much smaller and must be more carefully regulated. When preparing for brazing, the pieces may be placed together in exactly the right position, and brass provided for the joint in the shape of rolled or sheet brass placed over (or in) the crack between the pieces. The flux is added, and the heating done in the usual way.

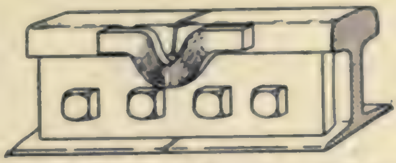

Fig. 29. Rail Bond Sweated against the Side of the Rail Head on Outside of Track.

Rail Bonding. A modification of the welding process is sometimes used for fastening bonds to the sides of rails, joined by the old fish-plate method, in order to make a continuous electrical conductor. In this work, the current required being very light, all of the apparatus is carried in one car. The work is really soldering, and not welding. The bonds are sweated against the side of the rail head on the outside of the track. Fig. 29 shows the shape and location of the bond used. The top of the bond is about flush with the top of the rail. The joint is sometimes touched up with a small portable hand-grinder, power for which is obtained from a wire fastened to a pole and hooked over the trolley wire. Fig. 30 illustrates the method of bonding a switch-piece.

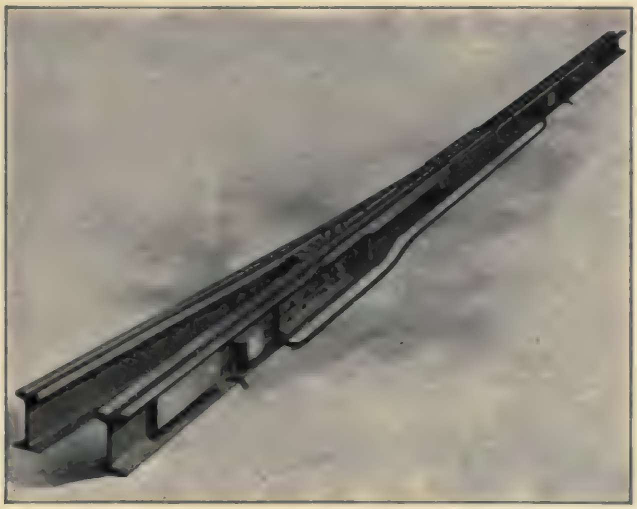

Fig. 30. Switch-Piece. Showing Method of Bonding around Same by means of Copper Cable with Ends Welded to Rail.

Power Required for Welding; Miscellaneous Data. It is almost impossible to give the exact amount of power required for welding work of a given section, without taking into consideration the shape of the section and the time taken. Both of these elements influence the results to a large extent. It is possible, however, to state certain rough general rules, and to set forth the results of commercial work and experiments, which will serve as a guide for approximately estimating the amount of power and time required.

The shorter the time taken, the less current is taken in proportion, as the heat is radiated only at a certain definite rate, and consequently less energy will be lost during a short time.

Sir Fred Bramwell* gives data from the results of an extensive series of experiments. The electrical readings were reported by Sylvanus P. Thompson; and in the discussion, considerable data on American practice were given by Professor Kennedy. The data given in the above paper met with the approval of Elihu Thomson, and may be taken as probably representing good practice.

The particular form of electrical energy needed is large current and low pressure, as the pressure (voltage) has nothing to do with the heating property of the current, merely serving to force it through the metal.

Experiments on a number of welds with round iron $1\frac{1}{8}$ inches in diameter gave the following results:

Average time, $2\frac{1}{4}$ minutes, found by taking the total time, and dividing by the number of welds made.

Actual time the current was on, about 26 seconds for each weld.

About 23.6 horse-power was required, this being the total load on the engine and including the engine, dynamo, and transformer losses.

Table II, compiled by S. P. Thompson, gives the results from readings taken between generator and welder, thus including the loss in the machine and welding transformer only. *Average* results are given, but the individual readings did not vary much from the average.

Exact proportions between power required and cross-sectional area cannot be given, as radiation has considerable to do with the power absorbed, and a thin rectangular bar will radiate heat faster than a round one of the same area.

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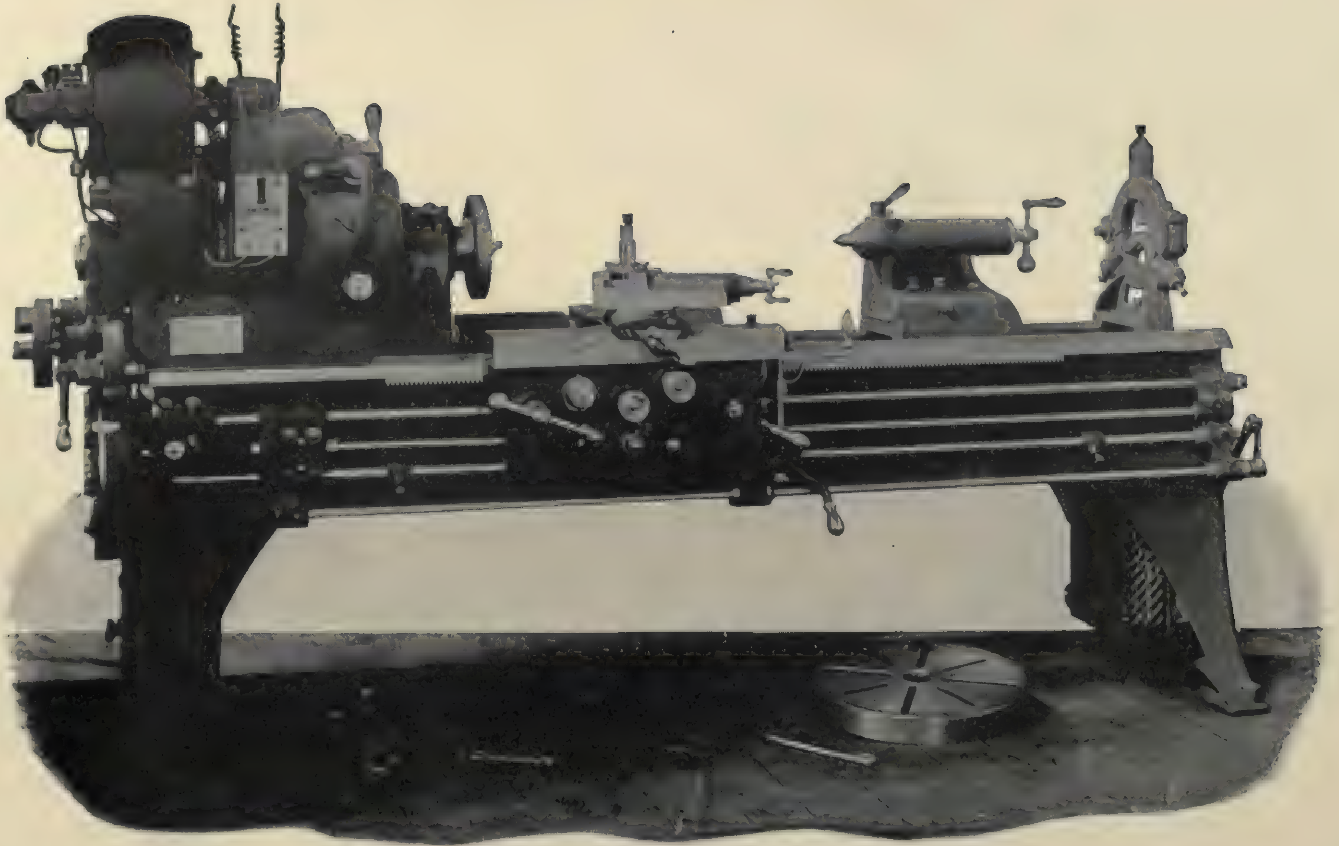
* Proceedings of the Institution of Civil Engineers of Great Britain, Paper No. 2460.



LATHE WITH SINGLE-VOLTAGE FIELD-WEAKENING MOTOR.

Controller Operated by a Handle on the Carriage.

TABLE II

Data of Welding Operations

Size of stock	1⅛ in. diam. Wrought Iron	¾ in. diam. Steel	2½ in. by 1⅛ in. Wrought Iron
Time current was on (seconds)	32	16	28.5
Power used (kilowatts)	13.17	11.4	24.98
Power used (horse-power)	17.5	15.2	33.4
Area of section (square inches)	1.00	.44	2.81
Horse-power used per square inch	17.5	34.5	11.8

Kennedy gives the following as American practice:

Standard projection of each piece from jaws of welder, distance equal to diameter, making distance between jaws of welder equal to twice diameter of work.

Standard time for 1-inch bar, 40 seconds; other sizes in proportion.

Length of part heated, to vary about as the diameter.

Horse-power to vary about as the square of the diameter, horse-power per square inch to remain constant.

As the result of a series of experiments the horse-power per square inch is given as follows:

1-inch bar, wrought iron	20.0	Horse-power
¾ " " " "	19.3	"
½ " " " "	20.4	"
1 " " steel	23.4	"
¾ " " "	20.5	"
½ " " "	19.6	"

This makes the horse-power per square inch practically constant; but it will be noted that no account is taken of the time, which may be varied in such a way as to make the horse-power always constant.

The above data gives enough information to enable the making of a fairly accurate estimate of the amount of power required in any particular case.

Another method of estimating, given by Mr. Hermann Lemp in *Engineering Magazine*, is based on the assumption that it takes about 7 horse-power-minutes to raise one cubic inch of metal to the welding temperature. This is practically the same for copper, brass, and iron—with the distinction, however, that for metals which conduct heat easily, a shorter time and correspondingly greater current strength must be used to prevent excessive loss from radiation and conduction. When the pieces are both short and wide, making the conduction by the clamps great, from 10 to 15 horse-power-minutes per cubic inch are required.

Axle and Tire Welding. The figures given in Table III are based on data given by Mr. Fred P. Royce in *The Iron Age.*

TABLE III

Axle and Tire Welding

AXLE WELDING

Size Stock	Power Used	Time	Area in Sq. In.	Power Used per Sq. In.
1 -in. round	25 H.P.	45 sec.	.785	32.0 H.P.
1 -in. square	30 "	48 "	1.000	30.0 "
$1\frac{1}{4}$-in. round	35 "	60 "	1.227	28.5 "
$1\frac{1}{4}$-in. square	40 "	70 "	1.563	25.6 "
2 -in. round	75 "	95 "	3.142	24.0 "
2 -in. square	90 "	100 "	4.000	22.5 "

TIRE WELDING

Size Stock	Power Used	Time	Area in Sq. In.	Power Used per Sq. In.
1 -in. by $\frac{3}{16}$ in.	11 H.P.	15 sec.	.198	58 H.P.
$1\frac{1}{4}$-in. by $\frac{3}{8}$ in.	23 "	25 "	.470	49 "
$1\frac{1}{2}$-in. by $\frac{3}{8}$ in.	20 "	30 "	.561	36 "
$1\frac{1}{2}$-in. by $\frac{1}{2}$ in.	23 "	40 "	.750	31 "
2 -in. by $\frac{1}{2}$ in.	29 "	55 "	1.000	29 "
2 -in. by $\frac{3}{4}$ in.	42 "	62 "	1.500	28 "

The radiating effect of the thin flat section is well illustrated by the 1 in. by $\frac{3}{16}$ in. tire, where 58 H. P. per square inch was required to make the weld; while with the comparatively heavy 2 inch by $\frac{1}{2}$ inch tire, the power was much less, being only 29 H. P. per square inch.

It will be noticed from Table III, that a greater amount of power per square inch is required to weld pieces of small area than those of larger section.

A safe rule to follow on average work would be to allow about 40 H. P. per square inch on pieces of from .05 square inch in cross-section to about .75 square inch; while above this size, from 30 to 20 H. P. would seem to be about right, depending on the shape of the section, 30 H. P. to be used for flat sections, and 20 H. P. for sections approximately round or square.

TABLE IV

Power and Time Requirements for Electric Welding of Round Iron or Steel Bars and Heavy Iron Pipe

ROUND IRON OR STEEL

DIAMETER	AREA	H. P. APPLIED TO DYNAMO	TIME IN SECONDS
¼ in.	.05	2.	10
⅜ "	.10	4.2	15
½ "	.20	6.5	20
⅝ "	.30	9.	25
¾ "	.45	13.3	30

EXTRA HEAVY IRON PIPE

INSIDE DIAMETER	AREA	H. P. APPLIED TO DYNAMO	TIME IN SECONDS
½ in.	.30	8.9	33
¾ "	.40	10.5	40
1 "	.60	16.4	47
1¼ "	.79	22	53
1½ "	1.10	32.3	70
2 "	1.65	42	84
2½ "	2.25	63.7	93
3 "	3.	96.2	106

TABLE V

General Table of Power and Time Requirements for Electric Welding of Iron, Steel, and Copper

IRON AND STEEL			COPPER		
AREA IN SQUARE INCHES	TIME IN SECONDS	H. P. APPLIED TO DYNAMO	AREA IN SQUARE INCHES	TIME IN SECONDS	H. P. APPLIED TO DYNAMO
0.5	33	14.4	.125	8	10.
1.	45	28.0	.25	11	23.4
1.5	55	39.4	.375	13	31.8
2.	65	48.6	.5	16	42
2.5	70	57.0	.625	18	51.9
3.	78	65.4	.75	21	61.2
3.5	85	73.7	.875	22	72.9
4.	90	83.8	1.	23	82.1

General Tables of Power and Time Requirements. The data in Tables IV and V are given by the Thomson Electric Welding Company, and may be taken to represent current practice on commercial work.

It will be noted that the power as given is the power required to run the *dynamo*, and thus includes all losses in dynamo, transformer, and welding machine proper.

COMMERCIAL WELDING

Electric welding has developed so far now that there are companies organized to do commercial welding on a large scale. In fact, many articles which are ordinarily very expensive to produce may be made very cheaply by this welding process. Cap screws, for instance, are now being made by a welding process, in place of the usual method of turning down the body from stock the size and shape of the head. By the old method, the shank of the bolt was turned down from bar stock of the same section as the head. When the shank was long, this necessitated an enormous loss of material. By the electric method, the head is made with a short stub for a shank, about a quarter-inch or so in length, and to this short stub is welded the finished shank in any length desired. Ordinarily cap screws are made of a sized stock which leaves a very small head, in order to save stock; but when the electric method is used, any sized head may be welded to the desired shank without loss of stock.

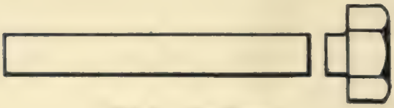


Fig. 31. Cap Screw.

In Fig. 31 is shown a sketch of a cap screw made in this manner, showing the parts before they are put together. The welding of course raises a burr, which may be removed easily by grinding or by taking a finishing cut in a lathe.

This method of welding has almost developed a new industry, as many parts are now made from forgings, which were almost impossible to make that way before on account of the enormous cost of the dies. Thus the cost of making the automobile forging shown in Fig. 32 would be almost prohibitive if forged in one solid piece; but by making in several pieces and then welding, the work is much simplified and the cost greatly reduced.

In Fig. 33 is another piece of work—a valve-stem for a gas engine—the making of which is much simplified by electric welding. If this piece were to be forged solid, it could of course be made in dies by drop forging; and while this is perfectly practicable when lots of several thousand are made at once, if only a few hundred or a few dozen are required, the welding process greatly simplifies the matter. The separate pieces may be made on the screw machine, and then welded and a cut taken to smooth up the stem.

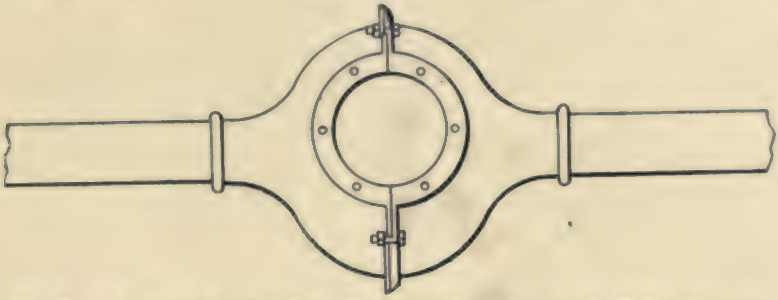


Fig. 32. Automobile Forging Made of Separate Parts Electrically Welded Together.

Still another sort of weld is shown in Fig. 13 where the work is shown after welding but before the burr has been removed.

Fig. 11 shows a weld in a section of clincher rim, a piece of work which it would be almost impossible to weld by any other method.

The applications of electric welding are almost unlimited, and in some fields have made possible work which otherwise might be impossible to accomplish. Many tools require a very hard cutting edge and a very tough shank; these may be obtained by welding a high-carbon steel for the cutting part of the tool to a low-carbon machine-steel shank. High-speed or air-hardening steel may be used in the same manner. This not only saves on the first cost; but a better tool is the result, as there is less chance of breakage in the shank.

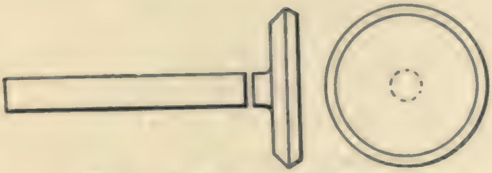


Fig. 33. Gas-Engine Valve-Stem.

Action of Various Metals in Electric Welding. Mr. Elihu

Thomson* gives some interesting data regarding the action of various metals in the electric welder:

> Tin can be welded with ease; also antimony and bismuth.
>
> Aluminum requires precautions; but welds can be made, and, when done right, the results are good. Hand electric welding is not good for aluminum; but with automatic machines, almost uniformly good results are obtained.
>
> Brass requires much greater current strength than wrought iron, although the specific resistance of cold iron is almost the same as that of brass. As the heat of the metal rises, however, resistance increases only slightly with brass and German silver, while the increase with iron is large.
>
> Brass seems to soften hardly at all when heated, passing almost immediately from solid to liquid, and, if too great pressure is used, will crumble and make a rather poor joint.
>
> Some bronzes—notably aluminum bronze—show some plasticity before fusion.
>
> Copper is a good conductor, and radiates heat easily. About one volt is required across terminals, and welding should be done rapidly in order to lose a minimum amount of energy through radiation.
>
> As a general rule, a flux should be used on metals whose oxides melt at higher temperatures than the metals. Brass should be fluxed, copper not. Covering action of flux is useful in most cases. No flux is required on soft iron; but heat which welds soft iron would ruin steel, so that flux is required on steel.

RECENT APPLICATIONS

One of the most recent and interesting applications of electric welding is that of making the side joints on ordinary hot-water tanks such as are found attached to kitchen stoves.

The following cuts and descriptive matter, for which the author is indebted to E. A. Suverkrop and the *American Machinist* is not only of interest on account of the process used, but also as giving a comparison of cost and strength between this and other methods of doing this sort of work.

The work described is done at the works of the John Wood Manufacturing Co., Conshohocken, Pa., where 800 to 1,000 boilers are made every twenty-four hours.

†The raw material in the shape of plates cut to size and varying in thickness from No. 16 to No. 9 Birmingham wire gauge—these are the thicknesses of the plates used for the boilers having electrically welded seams—are manufactured in the same town to special analysis.

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*Transactions of the Institute of Mining Engineers.

†E. A. Suverkrop, *American Machinist*, Feb. 25, 1909.

The requirements for this purpose demand an open-hearth steel possessing anti-rusting properties. It must be low in carbon, the analysis calling for 0.12 per cent, and the sulphur content must not exceed 0.03 per cent, while the tensile strength varies between 55,000 and 58,000 pounds per square inch.

The first operation is the rolling of the plates into cylindrical form which is done on the usual boiler rolls which are, of course, of a diameter to suit the work, the boiler shells ranging in diameter from 7 to 16 inches, and up to 70 inches in length. From the rolling operation the shells pass to the sand-blasting room where the usual low-pressure sand-blasting apparatus is used to remove the scale back on either side of the seam for about an inch and a half. The object of this is to give clean metal free from scale for the weld and also to facilitate the passage of the electric current, scale being a partial insulator of electricity. The plant which supplies current for the two welding machines consists of two 60-kilowatt Thomson alternating generators, specially wound for the purpose, delivering the current to the primary circuit at a voltage varying from 250 to 350, heavier work requiring the greater voltage, while for thinner work the primary voltage is reduced. The Thomson process of electric welding is used with modifications made necessary by this particular class of work. These modifications have been developed at this plant and are embodied in the two machines, built by the Standard Welding Company, Cleveland, O., shown in Figs. 34, 35, 36, and 37.

The machines are approximately 9 feet high, 6 feet wide, and 20 feet long over all. The machine proper consists of a heavy cast-iron base *B* upon which are mounted the pressure rolls or spools *A*, one on each side, and between which the boiler shell *C*, Fig. 36, passes during the welding operation. These rolls are made in pairs for the various sizes of boilers, are easily changed from one side to another, and are mounted so as to adjust to or from the center.

In front of the machine is a stake *D* which carries a horizontal bar *E*, upon the end of which is a head *F*, shown in Fig. 35, carrying three rollers, one roller on the top immediately below the two copper electrodes *G*, and the other two at an angle of about 120 degrees. These two lower rollers hold the boiler shell against the pressure rolls *A*, while it passes through the machine. Behind the machine, Fig. 35, is a device similar in construction to the regulation draw

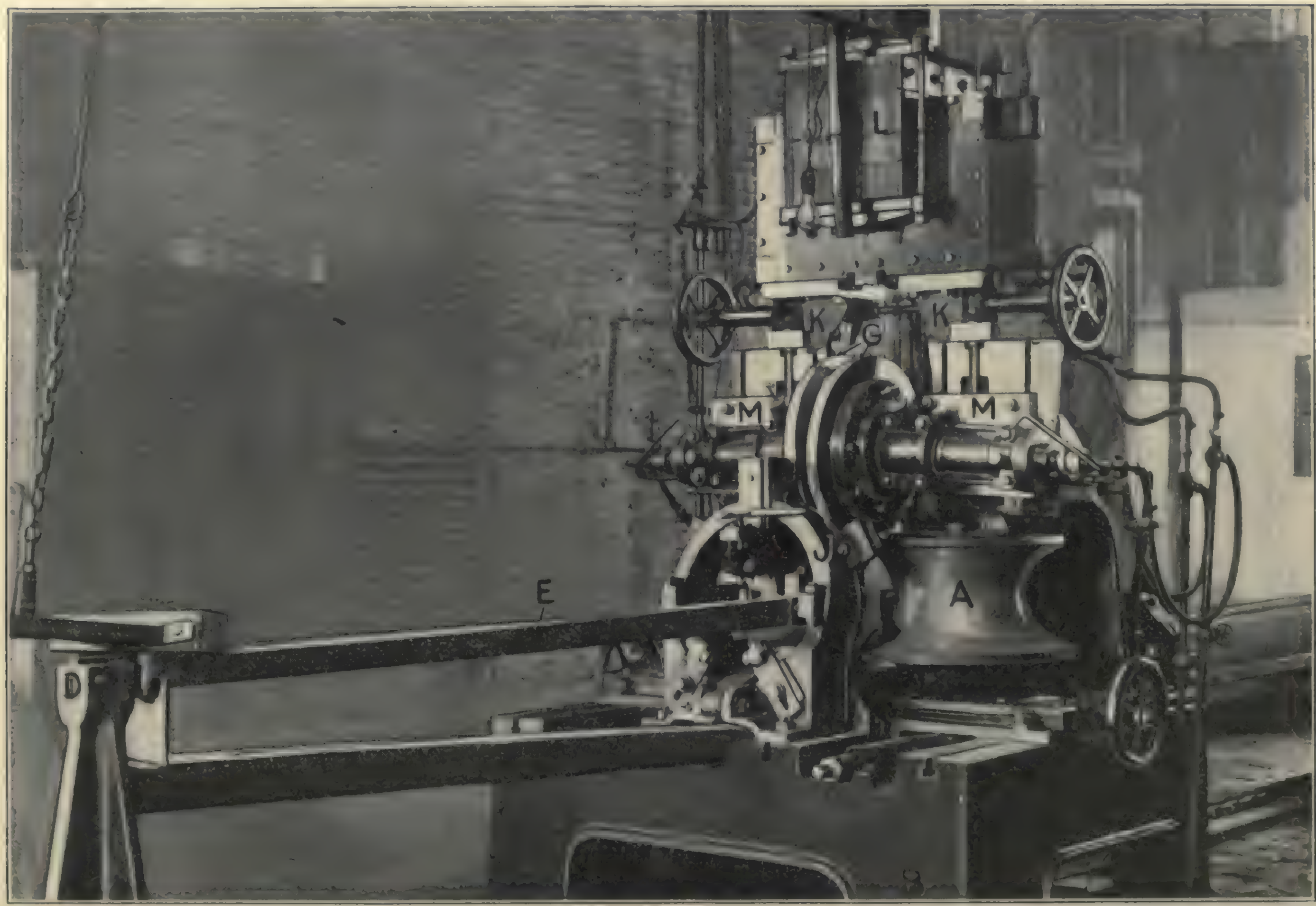


Fig. 34. Front of Electric-Welding Machine.

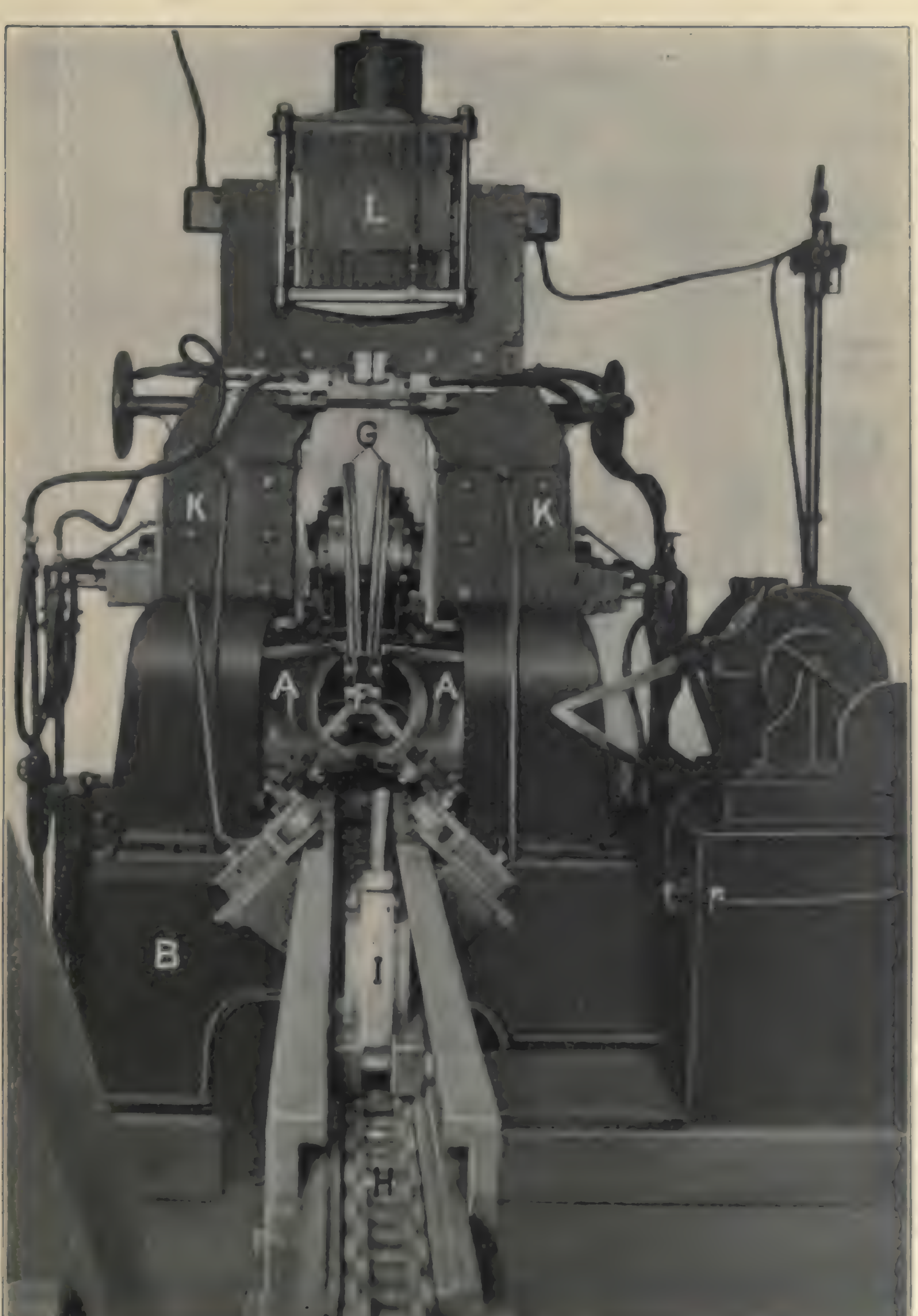


Fig 35. Rear View of Electric-Welding Machine.

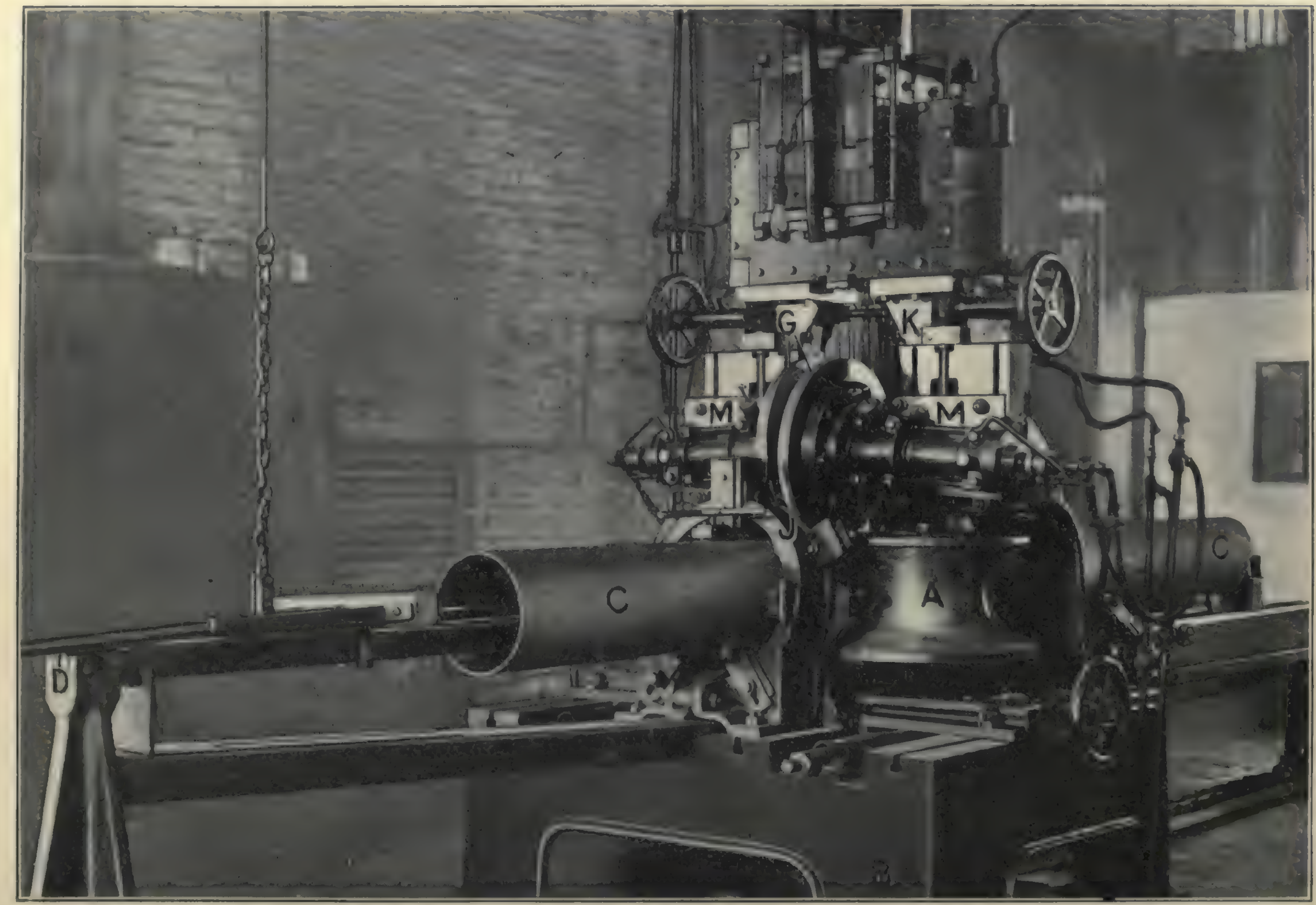


Fig. 36. Electric-Welding Machine with a Shell in Starting Position and One at Finished Position.

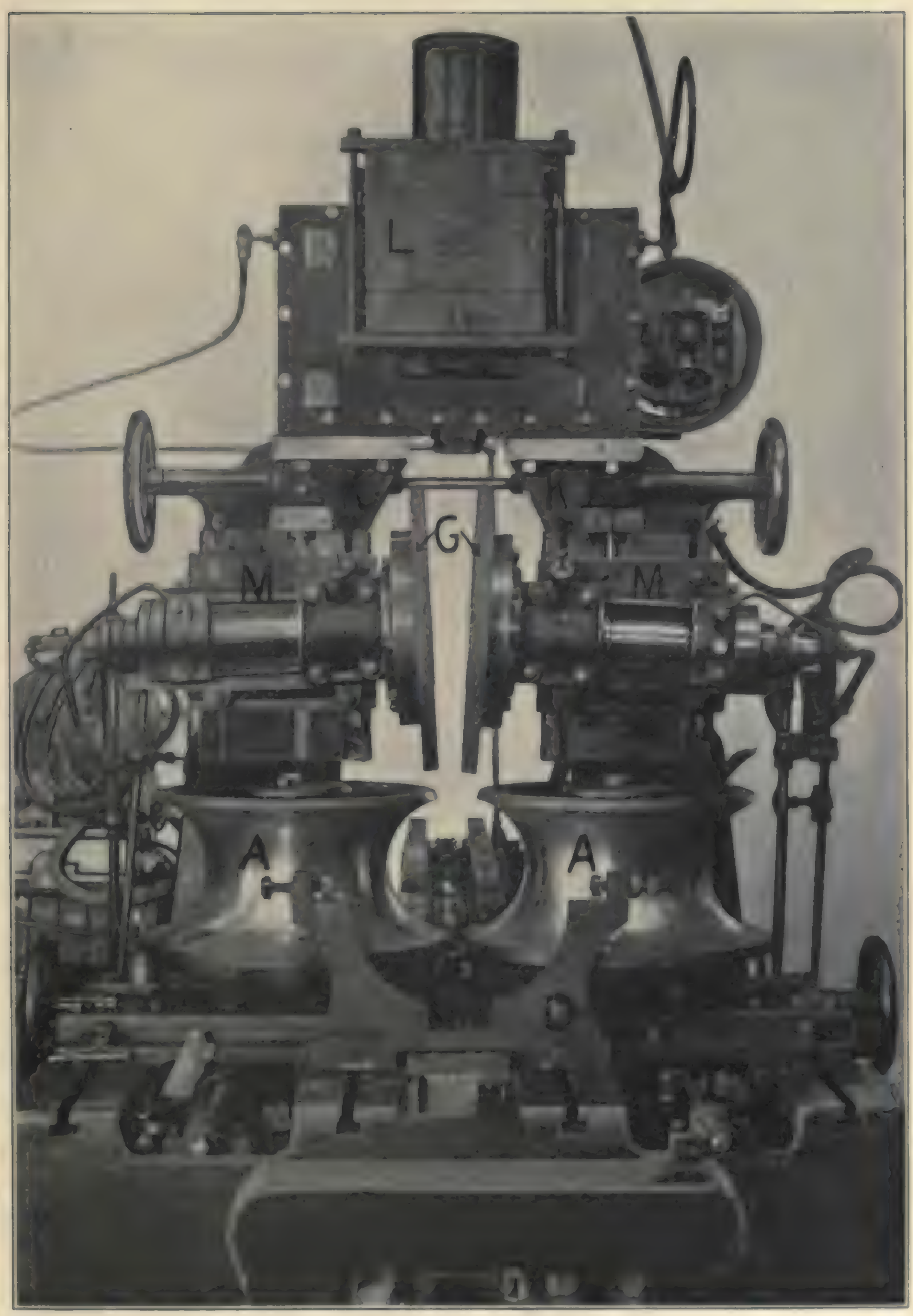


Fig 37 Front of Electric-Welding Machine with Yoke Removed.

bench, and having an endless chain *H* carried on pulleys at either end of a planed guide between which the chain runs.

The chain is attached to a carriage *I* provided with a gripping device which grips and draws the boiler shell between the pressure rolls during the welding operation. In front of the machine and secured to the base is a yoke *J*, Figs. 34 and 36, through which the boiler shell passes on its way to the pressure rolls and welding electrodes. The object of this yoke is to guide the shells and keep the joint exactly equidistant from each electrode during the welding operation, as the success of the weld depends to a great extent on the seam being guided in a straight line and half way between the electrodes. The yoke is provided at the top on the side next the machine with a thin blade of steel—not visible in the half-tone—which locates the boiler shell by the edges which pass one on either side of it. The yoke and other controls for the boiler shells are all within easy access of the operator.

Owing to the extreme flexibility of these thin boiler shells the adjustments and movements of the electric welding machines must of necessity be very exact and under instant and absolute control; a boiler shell 6 feet long taking but 22 seconds to weld from end to end does not permit of cut-and-try methods of adjustment.

Mounted on the base is the main frame *K* of the machine which carries at the top the transformer *L*, which is of the Thomson type. The primary circuit varies as previously stated, from 250 to 350 volts, depending on the character of the work; the transformer steps it down to from 25 to 45 volts, this also being governed by the character of the work.

The current is led from the transformer to the rotary electrodes *G* secured by bolts to gun-metal spindles approximately 4 inches in diameter, which run in gun-metal boxes in the heavy gun-metal saddles *M*. The saddles *M* are insulated from the cast-iron frame *K* of the machine by sheet mica, approximately $\frac{3}{16}$ inch thick.

The spindles which carry the electrodes are hollow to permit a circulation of cooling water which passes through the transformer and both spindles of each machine. The piping and valves show plainly in all the views. The cooling is necessitated by the heavy amperage, in the neighborhood of 24,000 amperes being required for electric welding.

The current passes from the saddles to the spindles or *vice versâ* at the point of contact, and among these points of contact are the two bearings. When the bearings become worn, slight sparking is liable to occur which has the tendency to make the bearings cut. But in spite of this sparking and the fact that gun metal and gun metal do not run well together, these bearings run from 12 to 14 months without renewing. When it does become necessary to renew the bearings, the spindle is so made that a new sleeve of gun metal can be driven on the spindle proper after the worn one is removed and the half bearings in the saddle and cap are readily replaced.

The electrodes *G* are copper disks secured to a flange on the spindle ends by tap bolts from the back. They are 1¼ inches thick, and about 26 inches in diameter. The spindles are inclined at such an angle that the electrodes, where they are nearest to each other, are about ¼ inch apart. This is at the point in contact with the boiler shell, and at this point the welding is performed. On the opposite side the disks are about 2½ inches apart.

The operation of the machine is as follows: The rolled boiler shells are lifted into the front of the machine with the seam up, as shown in Fig. 36, passed through the yoke, the small blade mounted on the yoke passing between the edges at the seam and locating the shell so that it will pass through with the seam equidistant between the two electrodes. The shell is then gripped by the clamp on the carriage *I*, Fig. 35, at the back of the machine and the draw bench started. This draws the shell backward between the pressure rolls and under the electrodes. The moment the seam strikes the electrodes, the current is switched on and the weld starts. As no instruments are used to determine the heat at point and time of weld, I cannot give any exact figures but a reasonable guess would place the temperature at about 2,800° F. The two edges are pressed together by the pressure rolls and the semi-fluid metal forms on the outside of the seam in the shape of a half-round bead running the full length of the welded shell.

From putting one 5-foot shell in until the putting in of the next, the elapsed time is about one minute, the actual welding taking but 22 seconds. The shell is red hot for a space only about ⅜ inch in width, and the blue color caused by the heat extends for less than an inch on each side of the weld. During the welding operation one can put one's finger on the shell 2 inches back from the red-hot weld and not feel that it is warmer than the surrounding atmosphere.

Owing to the shape and pressure applied to the shell by the electrodes and the roller on the inside of the shell, the finished product as it comes from the welder is out of round, being approximately as shown in Fig. 38, *A* being the weld, *A B* and *A C* are flat. The shells after leaving the welding machine, and previous to putting in the upper head, are rounded up to make them nearly true cylinders. This job is done very rapidly on a special machine built in the works.

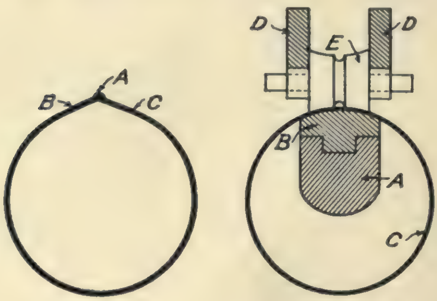


Fig. 38. Fig. 39.

Section of Shell and Rounding-Up Machine.

This rounding-up machine —shown partly in section in Fig. 39 — has a horizontal stake *A* with a planed surface on top to which various sized dies *B* can be readily fitted, the dies conforming to the inside curvature of the boiler shells *C* and being of a length greater than the longest boiler shell.

On either side of and above the stake are a pair of guides *D*, and at the front and back of the machine are a pair of idlers over which travel two parallel endless chains which are driven by a 7½ horse-power motor. These carry a rounding-up roll *E* conforming to the outside curvature of the boiler. The operation is as follows: The boiler shell is placed on the die on the stake with the welded seam up. The clutch is then thrown in and the rounding-up roller *E* is drawn by the chains on either side along the seam, guides *D* on top forcing it against the outside of the distorted boiler shell. One pass is sufficient to bring the shells to perfect cylindrical shape.

So far only the electric-welded shells have been referred to, but as I wish to compare them with riveted and oxyacetylene welded shells, I will state briefly the methods by which these two varieties of shell are produced. The sheets for the riveted shells are punched in the flat at both ends, but two strokes of a multiple punch being necessary. The rivets used are ⅜ inch in diameter and ¾ inch pitch. The sheets are then rolled to cylindrical shape, riveted, and then the seam is brazed. This takes about five minutes of time and 1½ pounds of brass at 13½ cents a pound.

The subsequent operations on these boilers are practically the same as those on the electric welded ones. The oxyacetylene flame has been described so many times that a repetition is not necessary here. The John Wood Manufacturing Company has a complete installation with two complete generating plants for oxygen and one for acetylene. They use it for welding heads to shells where this is ordered, but it requires too much space to apply to long seams.

Many tensile and vibratory tests have been made of electric welds made by this concern in various ways, plain butt welds, heavy butt welds—in which the plates were forced together so that a large amount of molten steel was raised on either side—and lap welds.

The percentage of defective welds made with the electric welding machine is about 0.1 per cent. In not one single case has an electric weld pulled apart at the weld. No piece tested has shown any crystallization either at the weld or at any place within the influence of the heat. All test pieces pulled apart at a point beyond the influence of the heat.

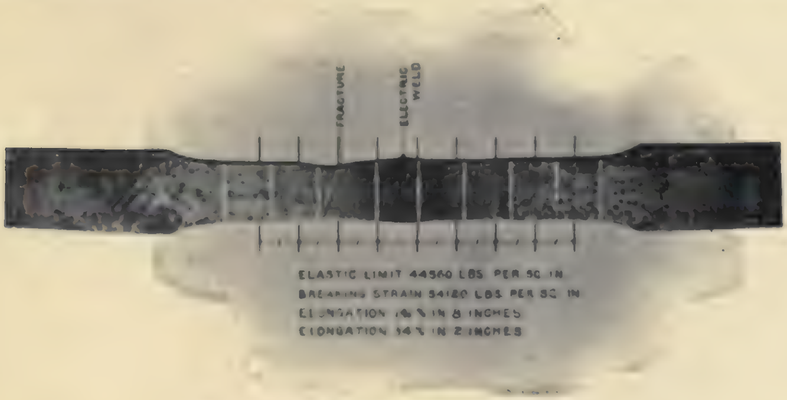

FRACTURE
ELECTRIC WELD
ELASTIC LIMIT 44560 LBS PER SQ IN
BREAKING STRAIN 54120 LBS PER SQ IN
ELONGATION 16 % IN 8 INCHES
ELONGATION 34 % IN 2 INCHES

Fig. 40. Typical Electric-Welded Test Bar.

The oxyacetylene-welded test pieces show a crystalline fracture, and, while the sectional area in the gas weld is increased 50 per cent, one of the test pieces failed partly in the weld. The tensile strength of the gas weld is good, but it does not stand up well under the vibratory test. The riveted and riveted and brazed seams invariably pull apart at the rivets. Fig. 40 shows a typical test bar, the fracture occurring beyond the influence of the heat.

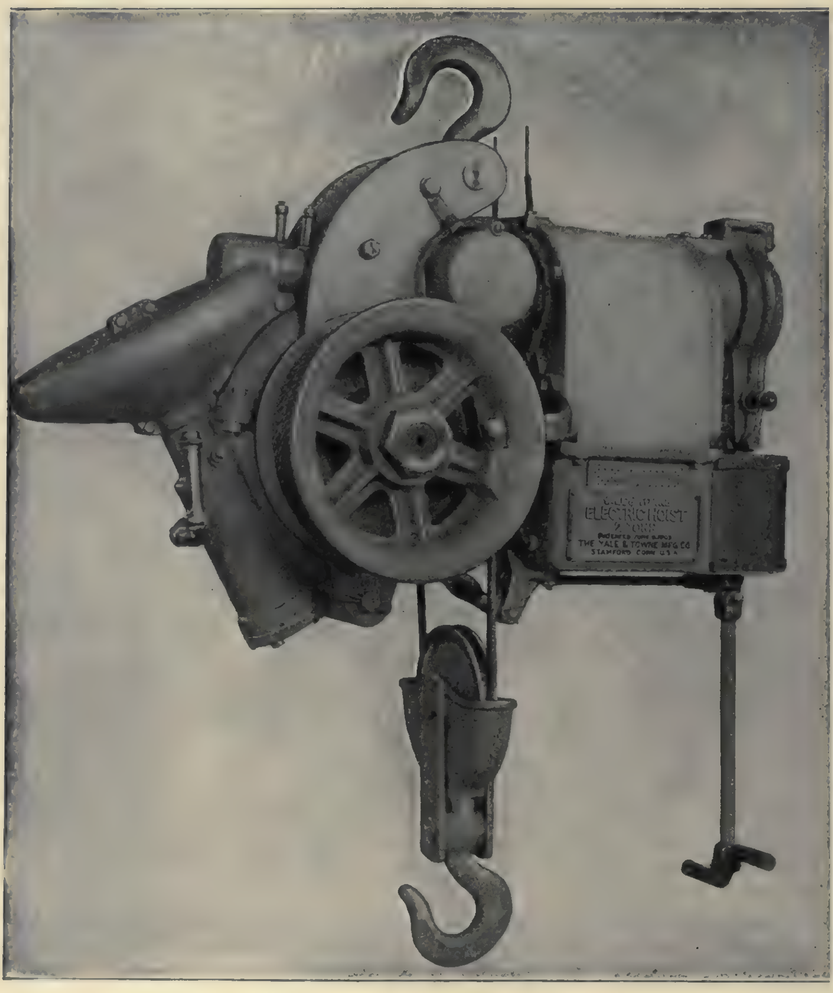
Table VI shows a series of tests giving about average results. The plain riveted and riveted and brazed seams both failed at the rivet holes. The gas weld failed partly at the weld and then the fracture ran at an angle. The electric welds failed beyond the part heated by the electrodes.

TABLE VI

Tests of Riveted, Riveted and Brazed, Gas-Welded, and Electric-Welded Seams

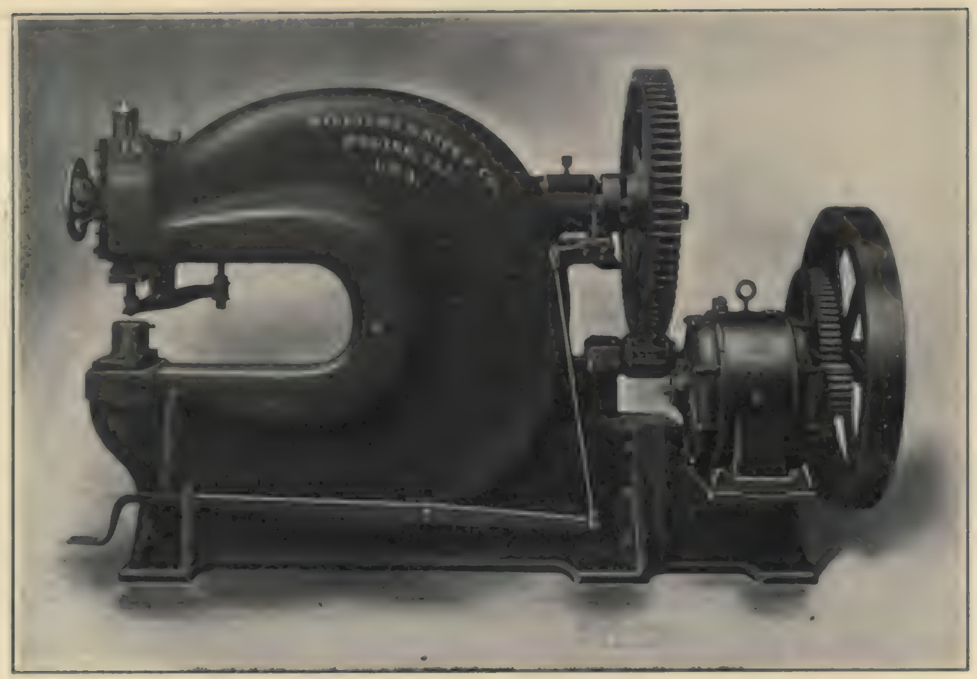
Test No.	Section, Orig.		Area, Orig.	Elastic Limit, Per Sq. In.	Ultimate, Per Sq. In.	Elongation. Per Cent In.		
						8″	2″	
1	2.66	0.084	0.223	43,230	45,520	2.5	7.0	Plain riveted
3	2.82	0.100	0.282	37,450	56,210	13.8	15.0	Riveted and brazed
5	2.30	0.085	0.195	45,800	59,640	17.0	26.0	Gas welded
7	1.923	0.081	0.156	42,570	50,130	2.0	5.0	Electrically welded
10	1.922	0.080	0.154	47,670	64,420	20.5	36.0	

Comparing the costs of the three methods of making the longitudinal seams, taking the electric weld as 1, the gas weld would be about 7.5, and the riveted and riveted and brazed seams about 10.



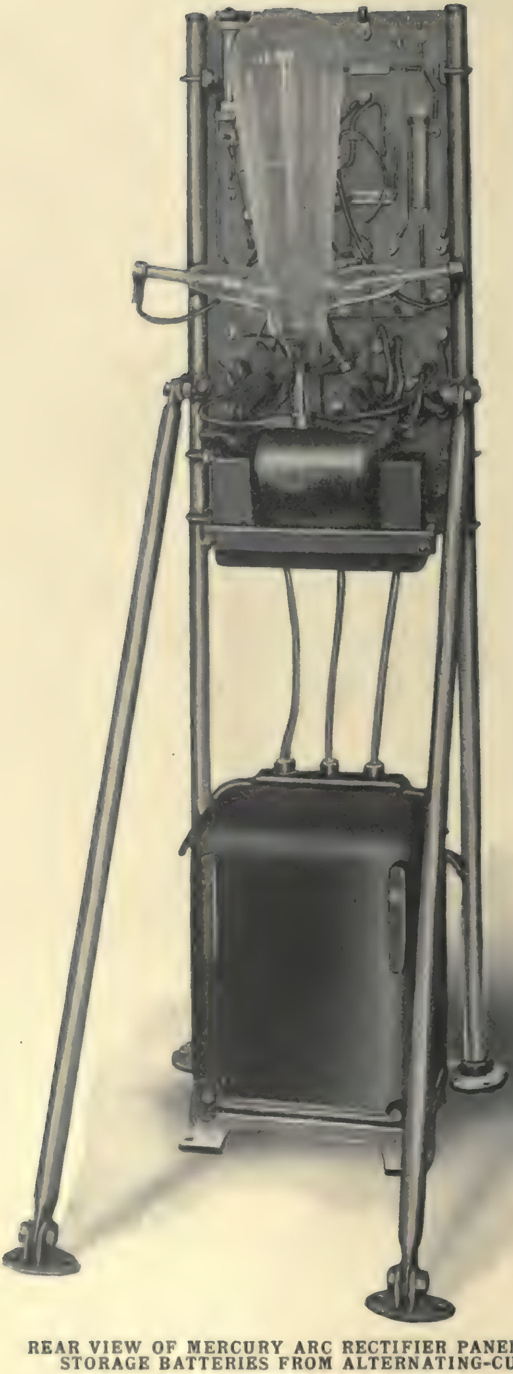
ELECTRIC PORTABLE HOISTING MACHINE.

Yale and Towne Mfg. Co.



WESTINGHOUSE MOTOR DRIVING THROAT PUNCH

Williams, White and Company.



REAR VIEW OF MERCURY ARC RECTIFIER PANEL, FOR CHARGING STORAGE BATTERIES FROM ALTERNATING-CURRENT MAINS

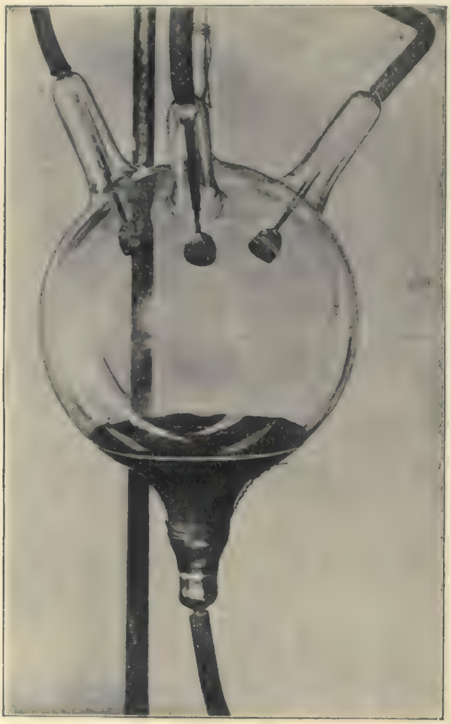
General Electric Company.

HEWITT MERCURY VAPOR CONVERTER.

The Mercury Vapor Converter is the result of the discovery of a new principle in the phenomena of electrical physics. This new principle, which concerns the passage of electricity through a vacuum tube or bulb, may be briefly explained. For electric current to pass through a vacuum, two electrodes are required—one to lead it in and the other to lead it out. These electrodes are merely electrical conductors exposed in the vacuum space. The electrode by which the current enters is called the *anode* or *positive*, and that by which it leaves, the *cathode* or *negative*. The positive and negative electrodes must evidently be connected, respectively, to the positive and negative supply lines. It is found by experiment, that, except under certain conditions, a very great resistance to the passage of current exists at the surface of the negative electrode of a vacuum tube, and that to operate all types of such apparatus (except under these peculiar conditions), this great resistance has to be continuously overcome by the application of a high electromotive force.

The necessary high electromotive force has usually been obtained from an induction coil. Little or no resistance to the passage of current is found at the anode, however. This surprising resistance to current flow which is found at the negative—called the "negative electrode resistance"—is so great under ordinary conditions that many thousand volts are required to overcome it. Strange to say, all that is necessary to practically eliminate this negative electrode resistance is to maintain the supply of current continuous after the current has once started. If the current is interrupted, *even for an instant*, or if it fall to a low value (say below one or two amperes), the negative electrode resistance will assert itself, and no current can flow.

It will be noted that in all vacuum tubes the current must be started by high potential or other means before the negative electrode resistance will disappear. In other words, whenever the initial negative electrode resistance is broken down, current will continue to flow, meeting only slight resistance until the current stops of itself, when the original initial negative electrode resistance will re-establish itself. The reason that older types of vacuum apparatus do not act in the same manner as Mr. Hewitt's tube, is that the supply of current is intermittent in its nature, and that the negative electrode resistance is being continuously re-established by the interruption of the current. Further, it is found that a liquid negative, such as mercury, is the only one that will operate continuously without deterioration. The old types of apparatus practically all use solid negatives.



Three-Phase Mercury Vapor Converter as Originally Exhibited by Mr. Hewitt.

Fig. 1.

Mr. Hewitt discovered that current passing through a vacuum charged with mercury vapor causes this vapor to emit an intense light, with a comparatively small expenditure of energy. His discovery of how the negative electrode resistance can be eliminated, allowed him to make economical use of this very efficient and new method of producing light. Hence his mercury vapor lamp.

APPLICATIONS.

The great principle of the "negative electrode resistance" has thus been briefly explained. Various practical applications can be made of it, which may be summarized as follows:

1. Owing to the low *operating* "negative electrode resistance," a vacuum electric lamp can be economically used.

2. From the fact that an initial extra voltage is required to produce the state of low negative electrode resistance, a vapor converter can be constructed which will change alternating current into direct current

8. Owing to this same property, the apparatus can be used as a circuit breaker for alternating currents.

4. Owing to the combination of the two properties described above (1 and 2), the apparatus can be advantageously used as a discharge gap, sometimes called an *interrupter*, to replace the air spark gap commonly employed for wireless telegraphy and other purposes.

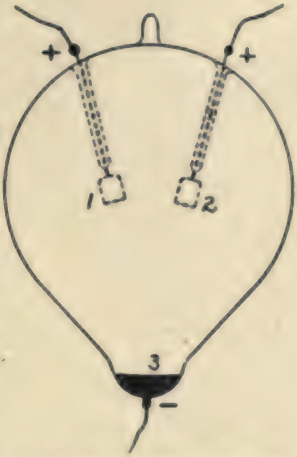


Fig. 2. Vapor Converter with Two Positive Electrodes.

DIRECT FROM ALTERNATING CURRENT.

To make clear the usefulness of the vapor converter, it will be necessary to state briefly the characteristics of alternating as distinguished from direct currents.

An electric circuit carries direct current when electricity passes in one direction continuously through the circuit. A circuit carries alternating current when at one moment electricity passes in one direction throughout the whole circuit, and at a later instant of time in the opposite direction throughout the whole circuit, and so on. Only direct current is suitable for charging storage batteries. Direct current is much more suitable than alternating for operating a great many classes of motors, such as elevator and hoisting motors, and, up to the present time, motors for street-car or railway work. It is found, however, that alternating current is very much more economical than direct current for transmitting and distributing electrical power. Consequently, since only direct current is suitable for many purposes, it will often be advantageous to be able to obtain direct current from alternating. This result can be accomplished, at the present time, by means of certain electrical apparatus called the "rotary converter," which is very similar to an electric generator or motor, but which is large and expensive, requires expert handling, and is not particularly efficient. It is the function of the vapor converter to provide a more satisfactory method of obtaining direct current when only an alternating-current service is available.

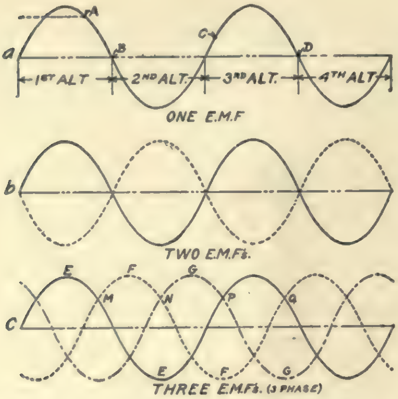


Fig. 3. Curves Representing Single-Phase and Polyphase Electromotive Forces

In the diagram *a*, Fig. 3, are shown the variations of ordinary alternating current or alternating electromotive force. Consider that in this figure the distance of the curved line above or below the horizontal line indicates the strength of the current or voltage at any particular instant of time, and that the further we go to the right on the horizontal line, the later the instant of time indicated. When the curve is above the horizontal line, the current in the circuit, or the electromotive force, is in one direction, and when the curve is below the horizontal line, it is in the other direction. It will be noticed that in changing from one direction to the other, the value of the current or voltage gradually decreases to zero, and then increases in the other direction up to a maximum, when it again decreases to zero and returns to its original direction, and so on.

Let us now consider the Hewitt apparatus. This may be briefly described as a large glass bulb or globe, with a small puddle of mercury at the bottom constituting the negative electrode, and, supported from the top part of the bulb, two or more electrodes of iron or other material. These electrodes are of various shapes, and usually not over one or two inches in size. Platinum lead wires run from all the electrodes to the outside line wires, through the glass, which makes a perfectly air-tight joint with this metal. The bulb is exhausted as perfectly as possible of all gases except mercury vapor. A converter of this type is shown in Fig. 1. In some cases it is desirable to make the electrodes all of mercury. Such a converter, with four positives and a negative, is shown in Fig. 8.

On account of the nature of the negative electrode resistance, if we connect a Hewitt mercury vapor apparatus across suitable direct-current mains, and start it by breaking down the negative electrode resistance, current will flow steadily until it is stopped by means external to the apparatus, this being the proper operation of the apparatus on direct current for giving light.

Suppose, however, we suddenly change the direct current to alternating current. At the instant of change, nothing new occurs. There is no difference in the operation of the apparatus, since we shall assume there is at the instant no change in the current. Then, referring to Fig. 3, at point A, where we shall assume the alternating current begins, it will be observed that the value of current begins to decrease, until finally a zero point is reached at B. At this time, of course, current ceases to flow. Meanwhile the alternating electromotive force or voltage is reversed, and begins to increase in strength. This reversal of direction makes the other electrode of the apparatus the negative; and, if we provide no means of overcoming its initial negative electrode resistance, no current can flow. The same condition will exist also when the alternating force has again become zero, and flows in its original direction, as indicated at the point C (Fig. 3). If the electrode resistance were broken down again at this point C, of course, the lamp would start again, and would run until the current again became zero at the point D. It is thus evident that this apparatus cannot run continuously of itself on alternating current.

Suppose, however, instead of the ordinary lamp, which has but two electrodes, we use an apparatus like that shown in Fig. 2, which has two electrodes at one end and one at the other. Suppose we pass direct current between electrodes 1 and 3 in such a direction that 3 is the negative or cathode. Then, as in the mercury vapor lamp, current will continue to flow between these electrodes; and the negative electrode resistance of electrode 3 will be practically eliminated by this current. Suppose, now, we apply, in addition to this direct current, the alternating electromotive force of Fig. 3 between electrodes 2 and 3. When the alternating electromotive force is at the point A, current will flow from 2 to 3, since 3, being the negative for the alternating current as well as for the direct, has no negative electrode resistance, on account of direct current which flows to it from electrode 1. As the alternating electromotive force changes to the opposite direction, it attempts to flow from 3 to 2; but, since in this case electrode 2 is its negative, and since its initial electrode resistance is not broken down, the reverse alternation of the alternating current cannot start. When the alternating electromotive force returns to its first direction again, however, 3 is its negative, and current will flow as before.

Thus only those alternations of the supply which have the direction from 2 to 3 can pass, and we have succeeded in getting one kind of direct current from an alternating source. The intermittent character of this current is shown at *a* in Fig. 5. This is perhaps the simplest form of converter. The direct current, however, though all in the same direction, is intermittent, and not well adapted for some kinds of work.

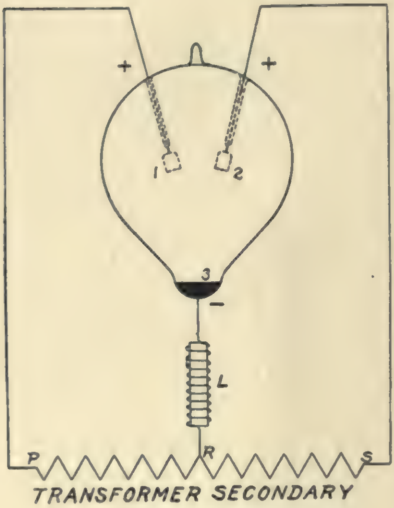


Fig. 4. Converter for Single-Phase Alternating Current.

Take another case. Suppose we have a second alternating current exactly opposite to the first, and suppose we have a fourth terminal in Fig. 2 similar to Fig. 1, and that the new alternating current is sent from the new electrode to 3. The relation of the two alternating electromotive forces is shown in Fig. 3. It is evident that the second alternating current, like the first, will pass only those alternations which are in the right direction, and that the others will be suppressed. But the former come just at the times when the first alternating current is not acting, so that the gaps of direct current left by the first are filled in by the second, and the current flowing in the negative is much more nearly steady than in the first case. This current is shown at *b* in Fig. 5.

Should the direct current from 1 to 3 be suddenly stopped, alternating current would continue to flow from 2 or from the extra electrode, whichever happened to be then operating, until the first zero point was reached, when, since both alternating electromotive forces are zero at the same time, all current would cease and the apparatus refuse to operate.

Now, suppose that the vapor apparatus shown in Fig. 1 be operated without direct current, and suppose that three different alternating currents be applied, each one between the negative and one of the three positive electrodes. These alternating electromotive forces are to be considered as three-phase electromotive forces —that is, each one lags $\frac{1}{3}$ of a complete double alternation behind the one before it, as shown in *c* (Fig. 3). Suppose the electromotive force E in this figure to be passing a current from its proper positive electrode to the negative in the three-phase converter, shown in Fig. 1. As this electromotive force becomes less and less until the point M is reached, the current through the converter would become less; but at this point the electromotive force F is seen to have risen to the same value in the same direction to which the electromotive force E has fallen; and thus, evidently, the electromotive force F, becoming greater than E, takes the current from E, and causes the current to increase in value again, following the curve F of the figure until the point N is reached, where the electromotive force G in turn takes the current away from F and carries it to the point P, at which the electromotive force E, having gone through a complete half-cycle, is ready again to take up the current from G and carry it to the point Q, and so on indefinitely. With this type of circuit there is evidently no time at which the current through the negative electrode becomes zero, and, consequently, the converter continues to operate indefinitely without the necessity of supplying direct current.

Such three-phase electromotive forces as are here described can be obtained from any three-phase circuit in which the neutral point is available. This is the type of converter first shown by Mr. Hewitt. It will readily be seen that in this case the direct current in the negative electrode—which is the current that is available for useful work—has a much steadier value than would be obtained by the apparatus of Fig. 2. Similarly, with an apparatus having still another positive electrode and four alternating-current electromotive forces, we should again have a converter in which the electromotive forces so overlapped as to require no direct current for bridging the zero points of the current. Such alternating electromotive forces can be obtained from any two-phase or ¼-phase circuit where the neutral point is available. In this apparatus the current in the negative is still more nearly steady than in the case of the three-phase converter.

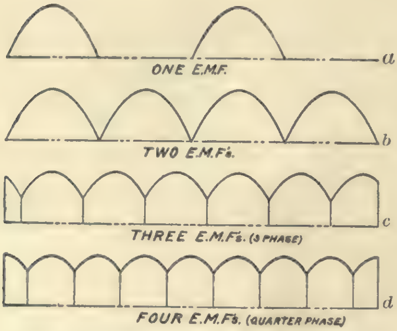


Fig. 5. Pulsations of Direct Current from Various Types of Alternating-Current Supply Circuits.

The currents from the different types of alternating-current circuit are compared as to steadiness in Fig. 5. In this figure it is assumed that there is no choke coil to smooth out the variations of the current; whenever such choke coils are used, the current is materially steadied.

On many alternating-current circuits, however, only one voltage is available, and there is no direct current for bridging the zero points as was found necessary in Fig. 2. For these cases, it is very desirable to have some means of operating a vapor converter. This can be accomplished by the apparatus shown in Fig. 4, which is the same as that of Fig. 2, except for the connection to the supply circuit, and except for the choke coil placed in lead from the negative electrode.

Referring to the figure, suppose that the voltage between the electrode P and the middle point R of the supply transformer be supplying current through electrode 1; this current is delayed behind the electromotive force, since it has to flow through the choke coil. This means that when the electromotive force from 1 has dropped to zero, the current has not yet reached zero, since it lags behind. The converter does not go out at this instant. It would, however, go out a little later, when the current finally did reach the zero point; but the electromotive force between the terminals

S and R, which is exactly opposite to that between P and R, is trying to force current from electrode 3 to electrode 1, and, on account of the lag of the current from 1, it will pick up this current before it becomes zero, and maintain it through the rest of the alternation, until this electromotive force in turn approaches zero. Again, since the current is lagging behind, the electromotive force between P and R will pick it up from R and S before it actually becomes zero, preventing the converter from stopping; and so on. The simple introduction of the choke coil enables the apparatus of Fig. 2, when supplied by the proper electromotive force from a single-phase circuit, to operate indefinitely without the use of auxiliary direct current. This is one of the most important applications of the converter. On account of the choking power of the coil, this arrangement gives quite a steady current; but, as in most of the cases above, it requires the neutral point of the alternating-current supply.

The vapor converter itself has a number of interesting characteristics. Its vacuum is similar to that of the mercury vapor lamp; on the other hand, since it is not intended to give light, its length is as short as possible; this means that the voltage across the converter, which represents its total resistance, is reduced to 10 or 15 volts. As in the mercury vapor lamp, this voltage is practically constant, regardless of current, except for small current. On the other hand, since with large currents in the container there is a considerable loss of energy, there is developed within the enclosing chamber a considerable amount of heat, which must be dissipated. It is therefore necessary to make the container itself of considerable size to get cooling surface; the mercury of the negative electrode is evaporated during the operation, and condenses on the surface, flowing back again to the electrode.

It is necessary to provide some means for the starting of the converter. This is accomplished in a number of ways, involving the same principles as the starting of the mercury vapor lamp. The converter can also be arranged to be started automatically.

These converters will be especially useful for charging storage batteries from alternating-current supply circuits; for running small direct-current motors; and, when built in larger sizes, for operating railway motors from alternating-current circuits.

AS A CIRCUIT-BREAKER.

The third application of the Hewitt mercury vapor apparatus is its use as a Circuit-Breaker for alternating currents.

It is of course necessary, in all electric plants, to have means for connecting and disconnecting motors, lights, circuits, etc., as may be required; and it is usually very desirable that means should be provided for automatically stopping the flow of current in any circuit when any accident occurs to the apparatus on this circuit. These functions are performed by many different types of switches and circuit-breakers, which on large high-tension plants, are very cumbersome and expensive, especially when automatic. In many plants, the size of the switching apparatus is so excessive that it is impossible to place the switches and circuit-breakers for operating the plant within view of the operator, who must rely on indicating devices to determine the condition of his circuits. On the principle of the mercury vapor apparatus, it is possible to construct a circuit-breaker which will accomplish this same work with a very much less cumbersome and bulky apparatus.

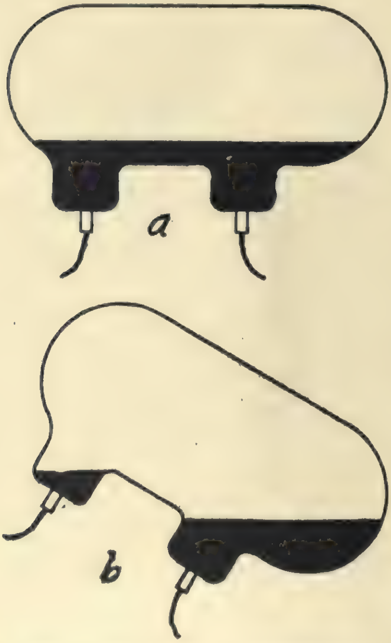
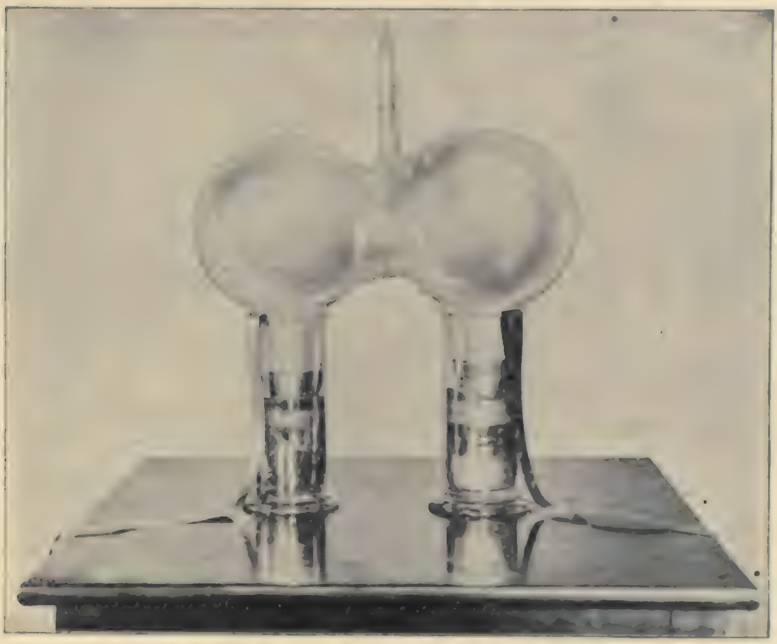


Fig. 6. Mercury Vapor Circuit-Breaker.
a—Circuit Closed.
b—Circuit Open.

To understand how the principle of the negative electrode resistance may be applied to this apparatus, we may consider the circuit-breaker in *a*, Fig. 6. Suppose that the current, in flowing from the generator to the circuit, passes through the vapor apparatus, going in by one lead, passing through the mercury from one cup to the other, and passing out on the other lead. We have thus an ordinary metallic circuit through the apparatus, and, as long as the circuit-breaker remains in this position, current continues to pass as though it were not a vacuum apparatus.

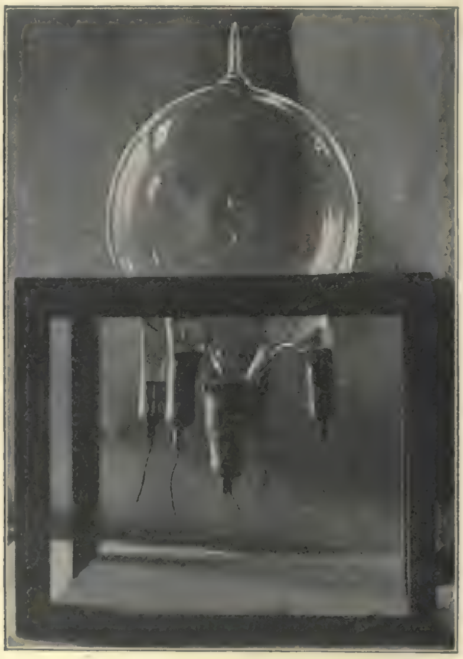
Next, suppose it is desired to stop the flow of current; the circuit-breaker is then tipped into the position shown in *b*, Fig. 6, in which the mercury separates between the two cups. At the moment of separation, the current, which has been flowing through the mercury from cup to cup, is obliged to pass through a portion of the vapor, making the mercury in one cup the negative electrode, and that in the other the positive, it being merely accidental which way the alternating current may happen to be flowing at the instant of the separation of the mercury. As was explained in the description of the mercury vapor lamp, when a separation is made between the negative and the positive electrodes which have been in contact and are carrying a current, the negative electrode resistance does not form, and the current passes freely through the vapor. The current breaker is thus for the moment operated as a mercury vapor lamp, and will continue thus to operate until the current



Mercury Vapor Discharge Gap for Heavy Current.

Fig. 7.

becomes zero. Since we are dealing with an alternating current, the current will become zero at the end of the first alternation; and when, in its natural course, the voltage rises in the opposite direction, the negative electrode resistance has become re-established, and current cannot flow. As a result, alternating current has been interrupted. As long as the circuit-breaker remains in the position of *b*, Fig. 6, no current will flow. However, if it be desired to start the flow of current again, it is necessary merely to tilt back the circuit-breaker into the first position, when, since mercury now joins the two cups, current will flow unimpeded as at first.



Converter with Four Mercury Positive Electrodes.

Fig. 8.

The mercury vapor device has other advantages over the present types of circuit-breakers, for all contacts are made by mercury which, being in a vacuum, cannot become corroded; consequently there are no bad contacts, and no solid switch-tips to become burred or burned. The whole apparatus is so small as to be readily operated automatically.

In the mercury vapor circuit-breaker, some interesting problems in construction arise. For example: It is difficult to get the current, when of considerable volume, from the external circuit, through the glass sealing chamber, to the mercury within, the difficulty being the tendency of the current to heat the leading-in wire, causing it to expand and crack the glass. It is possible, however, without serious mechanical complications, to introduce a very large current into the vacuum without causing any leaking seals.

AS A DISCHARGE GAP.

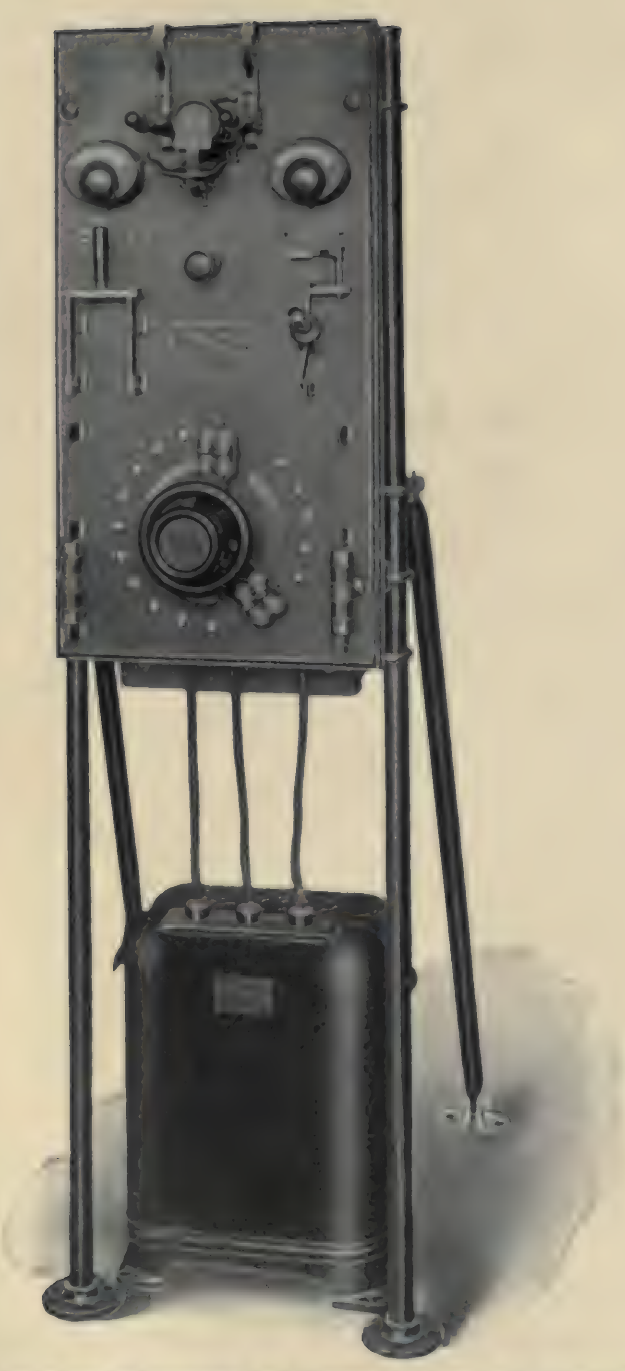
The fourth application of the mercury vapor apparatus, which has been frequently described in the technical press, is the Discharge Gap, sometimes called the *interrupter*. The function of the discharge gap is easily explained. For the production of X-rays, the sending of wireless telegraph messages, and many other purposes, it is necessary to have extremely sudden discharges of high-potential electricity. These are always obtained by introducing into the circuit from which the discharge is to be obtained, an air-gap or its equivalent, and by raising the voltage until this air-gap is unable to resist the strain, and breaks down. At this instant, there is a very sudden rush through the circuit of the electricity which has been previously accumulated on both sides of the air-gap; and this sudden discharge serves to send the wireless message, or excite the X-ray tube. But a disadvantage to be found with air-gaps is, that, even after they break down, they introduce a considerable resistance into the circuit, which prevents this discharge from being perfectly free as is most desirable. A further disadvantage to be met with in the air-gap is that an undesirably long time is required for it, when once it has been heated by the discharge, to cool sufficiently to be able to operate properly a second time. In addition, whenever these gaps are used for large quantities of energy, or continuously, the metal electrodes become scarred and burnt, and require constant replacing.

The mercury vapor apparatus shown in Fig. 7 may serve the same purpose as the air-gap, for, if we apply a comparatively low voltage between the two electrodes, no current will flow, because of negative electrode resistance, unless we raise the voltage sufficiently to overcome this resistance. Then the discharge of electricity will be practically free, since, when once broken down, the negative electrode resistance is substantially eliminated. Thus, by the use of the mercury vapor apparatus, the resistance to the discharge, introduced by an air-gap, is eliminated.

Furthermore, it is found by trial, that, even with a series of the most rapid discharges, the negative electrode resistance can always be re-established between them, which is by no means true of the air-gap. And again, evidently, the burning and burring of the electrodes of the air-gap are eliminated, as the mercury cannot corrode in a vacuum.

The action of the mercury vapor discharge gap has been carefully studied by the rotating mirror method, and has been found to be free in a remarkable degree from the weaknesses of the air-spark gap. Fig. 7 shows a discharge gap used by Mr. Hewitt in his laboratory on some of his high-tension work. These bulbs are about five inches in diameter.

In addition to the applications so far described, there are others of less immediate importance, which space will not permit to be described here. It must be remembered that the discovery of the great principle of the negative electrode resistance is quite recent, and that it is a radically new phenomenon, and consequently capable of producing most unusual results.



FRONT VIEW OF MERCURY ARC RECTIFIER PANEL, FOR CONVERTING ALTERNATING CURRENT INTO DIRECT FOR CHARGING STORAGE BATTERIES

General Electric Company.

REVIEW QUESTIONS.

PRACTICAL TEST QUESTIONS.

In the foregoing sections of this Cyclopedia numerous illustrative examples are worked out in detail in order to show the application of the various methods and principles. Accompanying these are examples for practice which will aid the reader in fixing the principles in mind.

In the following pages are given a large number of test questions and problems which afford a valuable means of testing the reader's knowledge of the subjects treated. They will be found excellent practice for those preparing for College, Civil Service, or Engineer's License. In some cases numerical answers are given as a further aid in this work.

REVIEW QUESTIONS

ON THE SUBJECT OF

DYNAMO-ELECTRIC MACHINERY

PART I

---

1. What was Oersted's discovery?

2. What is the relation between the direction of current flow in a conductor and that of the resulting magnetism?

3. What is meant by the expression *magnetic permeability*, and what formula really expresses its meaning?

4. What is the law of the magnetic circuit? Compare this law with that of the electrical circuit, and point out its similarity and dissimilarity.

5. Upon what does the reluctance of a magnetic circuit depend?

6. What do the magnetization curves of various samples of iron and steel show?

7. What does the expression *ampere-turn* mean?

8. Being given a ring of iron having a cross-section of 100 square centimeters and a mean length of 300 centimeters, determine the number of ampere-turns necessary to produce a total magnetic flux of 1,000,000 lines of force throughout the magnetic circuit. (Assume μ to have a value of 1,000.)

9. What is the effect of a joint in a magnetic circuit?

10. How does the pressure of an air-gap in a magnetic circuit affect the shape of the magnetization curve?

11. What is the meaning of the term *residual magnetism*? Is it of the same magnitude in the various magnetic materials?

12. What is the phenomenon of hysteresis, and what is its effect?

13. What are eddy or Foucault currents? How are they produced, and what is their effect?

REVIEW QUESTIONS

ON THE SUBJECT OF

DYNAMO-ELECTRIC MACHINERY

PART II

---

1. Upon what factors does the generated voltage of a dynamo depend?

2. Combine these various factors into an equation, and apply it in determining the voltage generated by a generator the armature of which is parallel-wound with 1,176 inductors, and which revolves in a 4-pole field at 1,200 r. p. m. Assume the flux entering or leaving the armature per pole to be 1,700,000 lines of force.

3. If the armature of a 10-pole generator is series-wound with 1,400 inductors, revolves at the rate of 400 r. p. m., and generates 150 volts, what is the flux entering or leaving the armature per pole?

4. What do you mean by the expression *efficiency of a generator*?

5. What is the difference between the terminal volts and generated volts of a generator?

6. An armature has an internal resistance of .05 ohm; it carries a current of 500 amperes; and the terminal voltage is 170. What is the generated pressure?

7. What are the objections to the general use of bipolar machines?

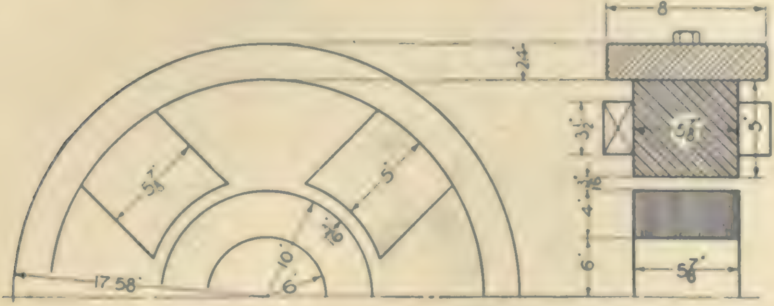
8. What are the advantages of "over-type" bipolar machines with respect to the "under-type?"

9. What are the general advantages of multipolar ring types of frames with respect to bipolar forms?

10. What is the meaning of the expression *magnetic leakage*, and how must we correct for it?

11. How does the magnetic flux divide in passing through the various parts of a multipolar machine?

12. Being given the magnetic circuit shown in the accompanying diagram, determine the number of ampere-turns required per pole to cause a flux of 1,800,000 lines of force to enter or leave the armature per pole. Coefficient of magnetic leakage = 1.15. The armature is to have 49 slots, and teeth of equal top dimensions, while the slots are parallel-sided and 1½ inches deep. The field-frame and pole-cores are of cast steel, and the armature cores of laminated wire, the effective length of which is 90 per cent.



13. If the machine of Question 12 is to generate 220 volts, is shunt-wound, and has a field-current of 1.5 amperes, determine the number of turns, size, and amount of wire employed per pole. Assume 20 volts allowed for field rheostat, and coil to be 3½ inches long.

14. What do you understand the terms *open* and *closed-coil* armature windings to mean? Which is it that is employed on constant-potential machines?

15. What is the relation existing between the number of armature coils and the number of commutator bars in the case of Gramme ring and drum-wound armatures?

16. What do you mean by *winding pitch?*

17. Why must the winding pitch be more or less than the number of slots divided by the number of poles?

18. Show diagrammatically what you mean by a *wave-wound* drum armature.

19. Show diagrammatically what you mean by a *lap-wound* drum armature.

REVIEW QUESTIONS

ON THE SUBJECT OF

DYNAMO-ELECTRIC MACHINERY

PART III

---

1. Why is it poor practice to use cast iron for the pole-cores of dynamo-electric machinery?

2. If wrought-iron pole-pieces are employed with cast-iron yokes, why should they be imbedded in the yoke?

3. What factor determines the cross-sectional area of the magnet-cores?

4. What factors determine the length of the magnet-cores?

5. What is the difference between *form-wound* and *bobbin-wound* magnet-coils?

6. What mechanical precautions must be taken in making up a field-coil winding and in bringing out the ends?

7. What are the advantages of form-wound coils over hand-wound coils for armatures?

8. Show by sketches the various methods of securing the armature laminations to the shaft, and point out the relative advantages and disadvantages of the different forms.

9. What is the object of ventilation ducts in armature cores, and how are they secured?

10. Why is the shaft of a dynamo-electric machine made larger than that for ordinary machinery, even though the weight supported is the same in both instances.

11. What is the object of using binding wires on an armature? Can their use be dispensed with, and how?

12. What material is usually employed for commutator bars, and why?

REVIEW QUESTIONS

ON THE SUBJECT OF

DIRECT-CURRENT MOTORS

1. State briefly the fundamental principle of the motor.

2. What is meant by the *torque* of a motor? How is it related to the power? If the field and armature current are constant, how is the torque related to the speed?

3. If the output of a motor is 60 horse-power, and the armature makes 490 revolutions per minute, what is the torque?

4. If the pulley of the motor in the preceding question is 22 inches in diameter, what is the effective pull upon the belt?

5. What is the commercial efficiency of a 500-volt motor which takes 120 amperes and delivers 71.6 horse-power?

6. What is meant by the counter-electromotive force of a motor? What relation does it bear to the efficiency?

7. The current in the armature of a shunt motor is 50 amperes; and the E.M.F. at the brushes, 240 volts. If the armature resistance is 0.38 ohm, what is the counter-E.M.F.?

8. Upon what does the speed of a motor depend?

9. Explain briefly the different methods used to vary the speed of shunt motors.

10. What disadvantages are there in controlling the speed of a shunt motor by a rheostat in the armature circuit?

11. A 230-volt shunt motor takes 55 amperes at full load, the speed being 760 revolutions per minute. What resistance must be inserted into the armature circuit to give half the full-load torque at two-thirds speed? How many watts are lost in this resistance under these conditions?

12. A shunt generator is to be used as a motor. What changes are necessary? Should the brushes be shifted, and, if so, to what point?

REVIEW QUESTIONS

ON THE SUBJECT OF

ELECTRIC WELDING

---

1. What are the three general methods of electric welding?

2. Make sketch of simple electric crucible.

3. Describe method of heating metal electrically in a bucket of strong brine.

4. What are some of the serious objections to welding in a forge fire that are overcome in the electric welding process?

5. Describe and explain the action of the current in automatically raising all parts of the joint to the same temperature when welding by the Thomson process.

6. Why is it economical to use as low a voltage as possible when welding by the Thomson method?

7. Why is it difficult to weld a piece of small cross section to one of larger section?

8. What are the particular advantages of electric welding of rails on electric traction roads?

9. Describe a welding train for track welding.

10. What is the cost for power (approximately) for making a welded joint in a rail such as described in the text? Assume that the grinding and sand blast apparatus are running practically continuously and just keep up with welder, and that the cost of current is 3 cents per K. W. hour.

11. What would be the cost of electrically welding rails 7″ girder type per mile of new track, at the usual contract price per joint, 60′ rails to be used and no allowance to be made for street work?

12. How can a bar be heated at one end only, in a Thomson welder?

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